FISHERY ECOLOGY OF SEYCHELLES' SEA CUCUMBER FISHERY

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DEDICATION

This dissertation is dedicated to my family, notably my grandfather Seiichi who have encouraged me to pursue my passion regardless of country borders. He often told me the stories of my ancestors going abroad to pursue their passion when Japan was just opening its boarder after 300 years of isolation. His stories of his father and grandfather's challenge in the time of letters, horses, and boats, were very good at making my worries look trifle when I felt overwhelmed with my work.

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perspectives of the fishery from all aspects including conservation, managaement, commercial, economy, and local livelihoods. This opened my eyes to how much impact one have to consider when managing a fishery and gave me the idea for some of my bio-ecnomic analysis in chapter 4.

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ABSTRACT

Sustainable fisheries productions have been an important factor for human livelihoods, yet the number of overfished fisheries have increased over the years. With strong market demand, sea cucumber fishery has a trend of initial rapid growth followed by a collapse due to the local depletion of the stock. Seychelles enjoys one of the few long-term tropical sea cucumber fishery owing to its strong management capacity. Using Seycelles as a case study, this dissertation explored possible sustainable management options for tropical sea cucumber fisheries. First, I studied the ecology of sea cucumber in Seychelles, then examined their fishery pattern, and determined the sustainable catch limit for the fishery. In Seychelles' unique granitic plateau system, most of the commercially targeted sea cucumbers were found in mid-depth zone. However, the depth range of these species were capped around 40m, where bottom substrate changed from sand to silt lacking biological cover. Marine protected areas in Seychelles were mainly designed to protect shallow coral reef habitat thus did not have significant effect in protecting the targeted sea cucumber species. The analysis of the fishery showed that fishermen have been fishing further from port and spent longer time at the sea. The target species have expanded to lower value species as the time progressed. Despite trip costs have increased from further fishing grounds and longer fishing days, fishermen's net gain per trip increased over the years since the market growth surpassed the trip cost increase. Combining the ecological findings and fishery pattern, I created a spatially explicit surplus production model to account for spatial expansion and different habitat quality across the Seychelles waters. The model showed that *H. fuscogilva* has hardly recruited from 2002 to 2011. The carrying capacity of the specie showed differences among depth and upwelling zone. Based on the extremely low recruitment rate, we propose that *H. fuscogilva* be removed from the list of species allowed to harvest in Seychelles.

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CHAPTER I

INTRODUCTION

1.1 General Introduction

For many years, sea cucumbers have been a popular delicacy in Japan, China, Korea, and Southeast Asia (Akamine 2001, Kinch et al. 2008, Manez and Ferse 2010). They are easily caught and have been commercially harvested in the Pacific for centuries (Conand 1990). They are especially sought after as a delicacy in Chinese cuisine known as beche-de-mer. Beche-de-mer is the boiled, dried, and smoked flesh of sea cucumbers that is often used to make soup and stir fry. Since the market value of beche-de-mer is extremely high, with values of up to 100 USD kg^{-1}, many coastal communities in tropical countries have established sea cucumber fisheries as an important source of income (Anderson et al 2011, Purcell et al. 2009), and these fisheries have played a significant role in poverty reduction in developing countries (Kinch et al. 2008). Ease of harvest has also played a role in female participation in often male dominated fisheries (Conand and Muthiga 2007). With the recent increases in economic growth in China and the broader Southeast Asia region, demand for beche-de-mer has increased dramatically (Conand 1998, Purcell 2013).

On pace with the global demand for beche-de-mer, sea cucumber stocks have experienced increased fishing pressure worldwide (Anderson 2011). Most tropical sea cucumber fisheries are small-scale and target multiple species, but despite this, such fisheries often easily become over-exploited due to several common factors including: (1) weak management capacity (Purcell 2013); (2) ease of harvest (Kinch et al. 2008); (3) slow growth of the animals (Conand 1989); and (4) low recruitment (Uthicke 2004, Hearn et al. 2005). In fact, many sea cucumber fisheries around the world have had a boom and bust history (Conand 1990, Anderson et al. 2011). The decimation of sea cucumber stocks has forced moratoria on fishing in places such as Australia, Mauritius, Mayotte (France), Papua New Guinea, Solomon Islands, Ecuador, and Venezuela (Purcell et al. 2013). The traditional fishing grounds for sea cucumber close to Asia have seen depletion and more recently, expansion of this fishing activity to new and more distant fishing grounds such as the Republic of Seychelles in the Indian Ocean has occurred (Bruckner et al. 2006, Toral-Granda et al. 2008).

There are at least 24 species of sea cucumbers inhabiting the Seychelles (Aumeeruddy and Skewes 2005). Among these, ten species (*Holothuria nobilis, H. fuscogilca, H. scabra, H. lecanora, Thelenota ananas, Actinopyga mauritania, A. echinitis, A. lecanora, A. miliaris,* and undescribed species “Pentard) are currently being commercially exploited for the export market (Aumeeruddy and Payet 2004, Aumeeruddy and Conand 2007). The Seychelles has seen rapid development of its sea cucumber fishery since 1990. By 1999, local stock depletion was noticed and the Seychelles Fishing Authority (SFA) implemented several management measures in response to this decline, including a licensing system for fishing and processing sea cucumbers, a quota on the number of fishing licenses allocated each year, and a limit of four divers for each fishing license (Aumeeruddy and Conand 2007). Despite the implementation of these management measures, signs of localized overexploitation are still apparent (Aumeeruddy and Conand 2007).

Overfishing of sea cucumbers will likely have negative impact on the productivity of the marine resource in the Seychelles since they play an important role in ecological function as bioremediators. Bioremidators reduce organic load, redistribute surface sediments, and enhance productivity of benthic biota through nitrogen excretion (Purcell et al. 2016). These functions are all important, particularly in oligotrophic waters such as coral reefs. Overfishing of sea cucumbers can lead to reduction in these ecological functions, impairing overall marine resource productivity.

To sustain its lucrative sea cucumber fishery and prevent negative ecological impact from the fishery, SFA was interested in exploring effective management options. This dissertation aims to help the management of the sea cucumber fishery in the Seychelles by: 1) studying their ecology, 2) studying the history and patterns of fishing effort and landing, and 3) conducting a stock assessment and create simulation models that allow the estimation of reference points to be used for management strategy evaluation (MSE).

1.2 Ecology of Sea Cucumber

Understanding the ecology of the animal is the first step in fishery management. The theory of density-dependent habitat selection has been well studied in the field of ecology, yet it has not been well applied to fisheries (MacCall 1990). It is important to understand the carrying capacity differences between areas when trying to calculate population size spanning large, heterogeneous areas. With fisheries management moving toward ecosystem-based approaches, the number of studies looking at interspecies interactions and spatial life history trajectories has increased (Walters and Martell 2004). Fishery independent-surveys are helpful to collect such information. Ecosystem-based fishery management (EBFM) has been promoted instead of the traditional single-species fishery management since managing the resource at the ecosystem level leads to more robust stocks and ecosystem services (Brodziak and Link 2002). EBFM emphasizes habitat and ecosystem function in the context of fluctuations, and suggests advanced models to incorporate spatial structure and environmental processes (Pikitch et al. 2004).

Fishery independent surveys also collect habitat data associated with the animal and its locations, and helps us understand the ecology and growth potential of a stock. For instance, if preferred habitat within the fishing grounds is limited, the potential growth of that stock will also be limited. Habitat information also aids in spatial management planning since managers can delineate the essential habitat for the stocks (Crowder and Norse 2008).

Another benefit of conducting fishery-independent surveys is that you can collect data to test hypotheses about density differences, regulation efficacies, and such. Marine Protected Areas (MPAs) and other access restricted sites are thought to protect exploited species by allowing the species to produce larger and more abundant individuals (refs). This, in turn, helps conserve fish stocks within MPA boundaries and provides fisheries benefits outside these protected areas through enhanced reproductive output and adult spillover (Nowlis and Friedlander 2005, Gaines et al. 2010). The Seychelles was the first country in the east African Region to create a MPA (1973), and currently has a network of 14 MPAs (Domingue et al. 2001). Deep non-divable sites are thought to function as refugia for sea cucumbers in the Seychelles since the sea cucumber fishery is all conducted exclusively by SCUBA diving. Therefore, both MPAs and deep sites are thought to act as refugia for commercially targeted sea cucumbers (Cariglia et al. 2013). Because of their potential to enhance fisheries, protected sites are often included in EBFM plans and spatially-explicit stock assessments (Halpern 2010, Johnson et al. 2013, Purcell 2010). In order to determine if the MPAs and deep area around the Seychelles are actually beneficial to the sea cucumber fishery and should be included in stock assessment models, efficacy of these refugia for sea cucumbers in the Seychelles were tested.

1.3 Seychelles' Sea Cucumber Fishery

Understanding the patterns and trends of a fishery is another important factor when considering management options. Even simple observation such as catch per unit effort (CPUE) change over time gives us some idea on the health of the stock and contributes to surplus production models. Catch rates (i.e., CPUE) can show at what stage of development the fishery is currently in, and can inform appropriate management actions (Hilborn and Walters 1992). However, using solely CPUE for management decision is not suggested. Additional knowledge such as history of the fishery (e.g., gear changes, vessel changes, and fishing pattern changes) and market (e.g., price changes, cost changes, and product changes) is critical for developing effective management solutions (Starr et al. 2010). Many conventional stock assessment models assume a stable fishery, and do not consider catchability changes (e.g. gear changes and technology improvements), target changes to lower valued species, cost changes (e.g. fuel and operation costs), and market changes (e.g. the price of the landing or additional market developments). However, all these elements commonly change in most fisheries and it is critical to know and document these changes to assess stocks accurately.

SFA has been recording landing and daily fishing effort for the sea cucumber fishery since 2000. These data include the number of each species caught, number of divers, fished depth, and area fished identified within 27 km grids. Additionally, SFA has installed vessel monitoring systems (VMS) on all sea cucumber fishing vessels to record the vessels' location hourly, giving us an unprecedented opportunity to study the spatial behavior of this small scale fishery. VMS is used primarily for fisheries enforcement purposes, but also provides high-resolution spatial and temporal fishing information. SFA have also collected exportation logs of sea cucumbers that have recorded market trends in detail. Since all harvested sea cucumbers in the Seychelles are exported, these export logs give us a rare opportunity to study stake holders' income trend associated with fishing pressure.

1.4 Fishery Management and Stock Assessment Models

Fisheries can be managed through various means, including: catch limits, gear restrictions, size restrictions, species restriction, and fishing ground restrictions. In order to carry out these management strategies, managers need clear quantifiable goals and rules so they can share their management vision with all stakeholders, and therefore make their decisions more transparent (Brodziak and Link 2002). Since management rules/goals require a great deal of investment, minimizing the risk of failure is important. The Food and Agriculture Organization of the United Nations (FAO) has proposed taking a precautionary approach (FAO 1996) when creating fisheries management goals, since it must consider many additional elements to the fishery (such as ecology, natural variability, and socio-economics). Under the precautionary approach, managers are required to indicate which management measures are to be applied and the circumstances under which the measures are to vary. This involves the formulation of decision rules, which specify in advance what action should be taken when specified deviation from the operational targets and constraints are observed (Punt 2006). In short, managers will have preset management actions under preset conditions (often defined by biological reference points), which reduces uncertainty. Stakeholders also benefit from this approach since it gives more certainty to their future by knowing what to expect (Punt 2006).

Reference points, such as maximum sustainable yield biomass (B_{MSY}) and harvest rate (H_{MSY}), have been used as the target of decision rules for many fisheries (Froese et al. 2011, Restrepos and Powers 1999, Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006). However, blind use of reference points as target without formal evaluation has also led to numerous fisheries declines (Mace 2001). To minimize this risk, use of simulation modelling has been suggested as a mean to assess the efficacy of these decision rules (Punt and Hilborn 1997). Unfortunately, very few stock assessments for sea cucumber fishery that allow for simulation modelling have been carried out to date (Skewers et al. 2014), although numerous ecological assessments and fishery analyses have been conducted (Anderson et al 2011, Friedman et al. 2011, Purcell et al. 2013). One factor contributing to this is the difficulty in obtaining growth and age parameters, which are required for age-structured stock assessment models. The sea cucumber's ability to shed tags and other foreign objects makes estimates of age and growth very problematic (Hamel et al., 2001, Battaglene and Bell 2004). Furthermore, sea cucumbers can cease feeding under adverse environmental conditions and can shrink in size (Sprung 2001) creating negative growth rates. In addition, most sea cucumber fisheries are small-scale industry or artisanal fisheries (Purcell et al. 2013) that often lack reliable fishery records, including catch and effort data needed for stock assessment. The Seychelles sea cucumber fishery is a rare exception in that reliable fishery records including VMS positions that can be used for stock assessment exist.

The challenges of estimating life history parameters of sea cucumbers have made it difficult to use age-structured population models, thus Bayesian surplus production model seems to be a better choice. Surplus production models are well suited for the Seychelles sea cucumber fishery since the minimum data requirement for the model is a time series of relative abundance indices and associated catch data (Haddon 2001). The model may lack the ability to describe the system in detail, but a simple stock production model can produce answers just as useful, and sometimes better for management than those produced by age-structured models at a fraction of the cost (Walters and Martell 2004). Furthermore, a Bayesian framework can reference multiple sources of data when estimating parameters that are preferable in stock assessment models. This allows the fishery models to include fishery-independent data along with fishery log-book (fishery-dependent) data. It is preferable to include fishery-independent data, since it does not have many of the biases associated with fishery-dependent data such as change in gear types, methods, and target species (Hilborn and Walters 1992).

1.5 Thesis Outline

The overall aim of this thesis was to use the Seychelles case study to improve the understanding of sustainable sea cucumber fishery management by investigating its ecology, fishery history, and building stock assessment model. To achieve this, the dissertation was divided into three chapters. Chapter 2 will discuss the ecology of sea cucumber in the Seychelles using the data collected from fishery-independent survey. This chapter described the density differences (hence carrying capacity differences) of sea cucumbers across different habitats and fishing pressures in the Seychelles so that stock assessment models can incorporate habitat variance in future assessments. This chapter also tested refugia efficacy in protected area and deep unfishable areas. Chapter 3 will describe the history of the fishery including landing trend, market trend, operation method change, CPUE trend, and spatially explicit fishing effort over time. Trends in landings, CPUEs, and fishing effort were examined to design the stock assessment model. Market trend was used to examine relationships with fishing pressure. Chapter 4 will use the findings from the first and second chapters and described a stock assessment model that allow reliable estimation of current stock size and life-history parameters needed for MSE.

References

Anderson, S. C., Flemming, J. M., Watson, R. and Lotze, H. K. (2011). Serial exploitation if global sea cucumber fisheries. *Fish and Fisheries*, 12, 317 – 339.

Aumeeruddy, R. and Conand, C. (2007). Seychelles' sea cucumber fishery: Data on processed products and other parameters. *SPC Beche de Mer Information Bulletin,* 26, 19-26.

Aumeeruddy, R. and Payet, R. (2004). Management of the Seychelles sea cucumber fishery: status and prospects. Advances in Sea Cucumber Aquaculture and Management. *FAO Fisheries and Aquaculture Technical Paper*, 463. Rome, FAO.

Aumeeruddy, R., & Skewes, T. (2005). Resource assessment of the holothurian populations in the Seychelles. *SPC Beche-de-mer Information Bulletin*, 21, 19-21.

Battaglene, S.C., Bell, J.D. (2004). The restocking of sea cucumbers in the Pacific Islands. In: Bartley, D.M., Leber, K.M. (Eds.), Marine Ranching. *FAO Fishery Technical Paper*, 429, 109–132.

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., ... & Weatherall, P. (2009). Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. *Marine Geodesy*, 32(4), 355-371.

Brodziak, J. (2007). An investigation of alternative production models to assess the Hawaiian bottomfish complex. Pacific Islands Fish. Sci. Cent., Natl. Mar. Fish. Ser., NOAA, Honolulu, HI.

Brodziak, J., & Ishimura, G. (2011). Development of Bayesian production models for assessing the North Pacific swordfish population. *Fisheries Science*, 77(1), 23-34.

Brodziak, J., & Link, J. (2002). Ecosystem-based fishery management: what is it and how can we do it? *Bulletin of Marine Science*, 70(2), 589-611.

Cariglia, Nicoletta, Shaun K. Wilson, Nicholas AJ Graham, Rebecca Fisher, Jan Robinson, Riaz Aumeeruddy, Rodney Quatre, and Nicholas VC Polunin. (2013). Sea cucumbers in the Seychelles: effects of marine protected areas on high- value species. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 23, (3), 418-428.

Clark, C. W. (1985). *Bioeconomic modelling and fisheries management*. Wiley.

Congdon, P. (2007). *Bayesian statistical modelling* (Vol. 704). John Wiley & Sons.

Domingue, G., Payet, R., and Shah, N. J. (2001). *Marine Protected Areas in the Republic of Seychelles.* A report prepared for the International Coral Reef Action Network (ICRAN) Project Eastern African Component. UNEP/FAO MT/1100-99-70.

Friedman, K., Eriksson, H., Tardy, E., & Pakoa, K. (2011). Management of sea cucumber stocks: patterns of vulnerability and recovery of sea cucumber stocks impacted by fishing. *Fish and Fisheries*, 12(1), 75-93.

Froese, R., Branch, T. A., Proelß, A., Quaas, M., Sainsbury, K., & Zimmermann, C. (2011). Generic harvest control rules for European fisheries. *Fish and fisheries*, 12(3), 340-351.

Froese, R. and Proelß, A. (2010) Rebuilding stocks until 2015: will Europe meet the deadline? *Fish and Fisheries*, 11(2), 194-202.

Gabriel, W. L., & Mace, P. M. (1999). A review of biological reference points in the context of the precautionary approach. In Proceedings of the fifth national NMFS stock assessment workshop: providing scientific advice to implement the precautionary approach under the Magnuson-Stevens fishery conservation and management act. *NOAA Tech Memo NMFS-F/SPO-40,* 34-45.

Haddon, M. (2001). *Modeling and Quantitative Methods in Fisheries*. Chapman and Hall, New York

Hamel, J. F., Conand, C., Pawson, D. L., & Mercier, A. (2001). The sea cucumber Holothuria scabra (Holothuroidea: Echinodermata): Its biology and exploitation as Beche-de-mer. *Advances in Marine Biology*, 41, 129-223.

Hilborn, R. (2010). Pretty good yield and exploited fishes. *Marine Policy*, 34(1), 193-196.

Hilborn, R., Pikitch, E. K., & McAllister, M. K. (1994). A Bayesian estimation and decision analysis for an age-structured model using biomass survey data. *Fisheries Research*, 19(1), 17-30.

Hilborn, R., and Waters, C. J. (1992). *Quantitative Fisheries Stock Assessment Choice, Dynamics, & Uncertainty*. Chapman and Hall, New York.

Honey, K. T., Moxley, J. H., & Fujita, R. M. (2010). From rags to fishes: data-poor methods for fishery managers. *Managing Data Poor Fisheries: Case Studies. Models and Solutions*, 159-184.

MacCall, A. D. (1990). *Dynamic geography of marine fish populations*. University of Washington Press, Seattle.

Mace, P. (2001). A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. *Fish and Fisheries*, 2, 2–32.

Maunder, M.N. (2008). Maximum Sustainable Yield. *Encyclopedia of Ecology*, 5, 2292-2296

Meyer, R., & Millar, R. B. (1999). BUGS in Bayesian stock assessments. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(6), 1078-1087.

Pella, J. J., & Tomlinson, P. K. (1969). *A generalized stock production model*. Inter-American Tropical Tuna Commission.

Prince, J., Hilborn, R. (1998). *Concentration profiles and invertebrate fisheries management. In Proceedings of the North Pacific Symposium on Invertebrate Stock*

Assessment and Management. Edited by G. S. Jamieson and A. Campbell. National Research Council of Canada. Ottawa. pp.187-196.

Punt, A. E. (2006). The FAO Precautionary Approach After Almost 10 Years: Have We Progressed Towards Implementing Simulation-Tested Feedback-Control Management Systems For Fisheries Management? *Natural Resource Modeling*, 19, 441–464.

Punt, A. E., & Hilborn, R. (1997). Fisheries stock assessment and decision analysis: the Bayesian approach. *Reviews in Fish Biology and Fisheries*, 7(1), 35-63.

Purcell, S. W. (2010). *Managing sea cucumber fisheries with an ecosystem approach*. FAO.

Purcell, S. W., & Kirby, D. S. (2006). Restocking the sea cucumber Holothuria scabra: Sizing no-take zones through individual-based movement modelling. *Fisheries Research*, 80(1), 53-61.

Purcell, S. W., Mercier, A., Conand, C., Hamel, J.-F., Toral-Granda, M. V., Lovatelli, A. and Uthicke, S. (2013). Sea cucumber fisheries: global analysis of stocks, management measures and drivers of overfishing., *Fish and Fisheries* 14, 34–59.

Purcell, S. W., Polidoro, B. A., Hamel, J. F., Gamboa, R. U., & Mercier, A. (2014). The cost of being valuable: predictors of extinction risk in marine invertebrates exploited as luxury seafood. *Proceedings of the Royal Society B: Biological Sciences*, 281(1781).

Restrepo, V. R., & Powers, J. E. (1999). Precautionary control rules in US fisheries management: specification and performance. *ICES Journal of Marine Science: Journal du Conseil*, 56(6), 846-852.

Richmond, R. H. (1996). Suggestions for the Management of Sea Cucumber Resources in Micronesia. *Technical Report 101*, University of Guam Marine Laboratory, November.

Simpfendorfer, C. A., Hueter, R. E., Bergman, U., & Connett, S. M. (2002). Results of a fishery-independent survey for pelagic sharks in the western North Atlantic, 1977–1994. *Fisheries Research*, 55(1), 175-192.

Skewers, Timothy, Eva Plaganyi, Nicole Murphy, Ricardo Pascual, and Mibu Fischer. (2014). *Evaluating Rotational Harvest Strategies for Sea Cucumber Fisheries*, CSIRO.

Smith, B. D., & Botsford, L. W. (1998). Interpretation of growth, mortality, and recruitment patterns in size-at-age, growth increment, and size frequency data. *Canadian Special Publication of Fisheries and Aquatic Sciences*, 125-142.

Sprung, J. (2001). *Invertebrates: A Quick Reference Guide*. Sea Challengers, Danville, CA.

Starr, Richard M.; Culver, Carolynn S.; & Pomeroy, Caroline. (2010). *Managing Data-Poor Fisheries Workshop: Case Studies, Models and Solutions*. UC San Diego: California Sea Grant College Program.

Taylor, S., Dennis, D., Haywood, M., & Donovan, A. (2006). *Sustainability assessment of the Torres Strait sea cucumber fishery*. CSIRO Marine and Atmospheric Research.

Toral-Granda, V., Lovatelli, A., Vasconcellos, M., Conand, C., Hamel, J. F., Mercier, A., ... & Uthicke, S. (2008). Sea cucumbers. A global review on fishery and trade. *SPC Beche de Mer Information Bulletin*, 28, 4-6.

Uthicke, S., Welch, D. and Benzie, J.A.H. (2004). Slow Growth and Lack of Recovery in Overfished Holothurians on the Great Barrier Reef: Evidence from DNA Fingerprints and Repeated Large-Scale Surveys. *Conservation Biology*, 18, 1395–1404

Walters, C. J., and Martell, S. J. D. (2004). *Fisheries Ecology and Management*. Princeton University Press, Princeton.

CHAPTER II

FISHERY ECOLOGY OF THE SEYCHELLES SEA CUCUMBER: DRIVERS OF ABUNDANCE

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Introduction

Sea cucumbers have long been a popular delicacy in Japan, China, Korea, and southeast Asia. They are easy to catch and have been commercially fished in the Pacific for centuries (Purcell et al. 2013). However, recent increases in demand, coupled with ease of harvesting, has led many local stocks to be overfished and some to be commercially extinct (Richmond 1996, Toral-Granda et al. 2008, Friedman et al. 2011). The traditional fishing grounds for sea cucumbers close to Asia have seen severely depleted and more recently, expansion of this fishery to new and more distant fishing grounds such as the Republic of Seychelles in the Indian Ocean has been noted (Toral-Granda et al. 2008).

The sea cucumber fishery in the Seychelles has existed since the 1950s (Aumeeruddy and Payet 2004), but has rapidly developed since 1990 when a new market was established in Singapore (marine product processor, personal communication). There are at least 24 species of sea cucumbers inhabiting the Seychelles (Aumeeruddy and Skewes 2005). Among these, ten species (*Holothuria nobilis*, *H. fuscogilva*, *H. scabra*, *H. lecanora*, *Thelenota ananas*, *Actinopyga mauritiana*, *A. echinitis*, *A. lecanora*, *A. miliaris*, and an undescribed species “Pentard”) are currently listed as commercially exploited for the export market (Aumeeruddy and Payet 2004, Aumeeruddy and Conand 2007). By 1999, local stock depletion was noted and the Seychelles Fishing Authority (SFA) implemented several proactive management measures in response. This included a limit on the number of fishing licenses allocated each year and a limit of four divers for each fishing license (Aumeeruddy and Conand 2007). Furthermore, all fishing vessel were required to have vessel monitoring system (VMS) to track vessels for safety and compliance. Despite the implementation of these management measures, signs of localized overexploitation were still apparent (Aumeeruddy and Conand 2007). SFA conducted a sea cucumber stock assessment in 2004 in collaboration with Food and Agriculture Organization of the United Nations (FAO) in order to propose catch limits for this fishery. However, catch limits proposed by SFA were not accepted by fishermen and therefore were not implemented. This rejection was due in part to mistrust of the surveys conducted by SFA and FAO. The proposed catch limit was also not conservative, since the stock assessment was solely based on abundance data from dive surveys and assumed stable fishery, which was not true for the Seychelles sea cucumber fishery.

There are several models used to conduct stock assessments depending on the type of data available. If managers have reliable abundance and catch data but no life history data, they should consider a surplus production model (Pella and Tomlinson 2002, Meyer and Millar 1999). If managers only have life history and population structure data, they can only consider per-recruit type analysis such as yield per recruit (Beverton and Holt 1957) and spawning potential ratio (Gabriel et al. 1989, Prince et al. 2015). If both abundance data and life history data are available, managers may think about fitting more sophisticated model such as age structured production models (Levin and Goodyear 1980).

Surplus production models are recommended for sea cucumbers, since it is extremely difficult to obtain essential life history information, such as growth rates, for these organisms (Uthicke et al. 2004a). Fortunately, SFA has been collecting detailed fishery logbook data since 2000, providing reliable abundance index and catch data needed to fit production models (Hilborn and Walters 1992). To make these production models more reliable, it is preferable to combine fishery data with fishery-independent surveys (e.g. dive surveys), as these surveys are not influenced by management regulations or socioeconomic factors (Haddon 2010). Furthermore, fishery-independent surveys can estimate actual stock size, whereas fishery dependent data can only estimate relative abundance.

Fishery independent -surveys are also helpful for stock assessment in ecosystem-based fishery management (EBFM) framework. EBFM has been promoted instead of the traditional single-species fishery management since managing the resource at the ecosystem level leads to more robust stocks and ecosystem services (Brodziak and Link 2002). EBFM emphasizes habitat and ecosystem function in the context of fluctuations, and suggests advanced models to incorporate spatial structure and environmental processes (Pikitch et al. 2004). Fishery independent surveys also collect habitat data associated with the animal and its locations, and helps us understand the ecology and growth potential of a stock. For instance, if there was only a small amount of preferred habitat within the fishing grounds, the potential growth of that stock may be limited due to carrying capacity. The habitat information also aids in spatial management planning since managers can delineate the essential habitat for the stocks (Crowder and Norse 2008).

Another benefit of conducting fishery-independent surveys is that you can collect data to test hypotheses about density differences, regulation efficacies, and such. Marine protected areas (MPAs) and other access restricted sites are often thought to protect exploited species by allowing the species to produce larger and more abundant individuals. This, in turn, helps to conserve fish stocks within MPA boundaries and provide fisheries benefits outside these protected areas through enhanced reproductive output and adult spillover (Nowlis and Friedlander 2005 and Gaines et al. 2010). The Seychelles was the first country in the east African Region to create a MPA (1973), and currently has a network of 14 MPAs (Domingue et al. 2001). Deep non-divable sites are also thought to function as refugia for sea cucumbers in Seychelles, since the sea cucumber fishery is all conducted by SCUBA diving. Therefore, both MPAs and deep sites are thought to act as refugia for commercially targeted sea cucumbers (Cariglia et al. 2013). Because of their potential to enhance fishery benefits, protected sites are often included in EBFM plans and spatially-explicit stock assessments (Halpern 2010, Johnson et al. 2013, Purcell 2010). In order to determine if the MPAs and deep area are actually beneficial to the sea cucumber fishery and should be included in stock assessment models, we tested the efficacy of these refugia for sea cucumbers in the Seychelles.

In order to maintain the lucrative sea cucumber fishery of the Seychelles, the government felt it necessary to set sustainable catch limits. In order to achieve this goal, while also instilling confidence in the fishing community that these limits were scientifically valid, the University of Hawaii, in collaboration with SFA, conducted a fishery-independent survey of the Seychelles sea cucumber fishery. The goals of the survey were to: 1) estimate stock size, 2) define preferred habitat of the species, 3) test refugia efficacy, and 4) analyze stock trend over time.

Method

We collected fishery-independent data using underwater visual belt transect survey techniques to collect information on species density, size, and habitat. Survey cruises were carried out between April-May of 2011, March-April of 2012, and March-April of 2013 to coincide with favorable weather.

Survey sites were grouped into two categories: general survey and MPA survey sites. Data collected from general surveys were used to: 1) estimate mean density, mean body size, and stock size of each species in Seychelles, 2) determine habitat preference of each species, 3) test the effect of fishing pressure and depth on species density, and 4) test the deep refugia hypothesis. Data collected from MPA survey were used to test the efficacy of MPAs in protecting sea cucumbers from fishing pressure. Lastly, we utilized FAO survey data conducted in 2004 to assess density changes over time.

Data collection

Survey site selection

Although the survey was initially designed to cover the entire plateau, the actual survey area was limited to waters within sight of the main granitic islands due to security concerns over piracy (Fig. 2.1). General survey sites were selected using a stratified random sampling design, where strata were based on cumulative fishing pressure and depth to ensure adequate sampling of all possible habitats (Fig. 2.1).

Depths were obtained from SRTM30_PLUS bathymetry data (Becker et al. 2009) with resolution of 30 arc seconds. Depth was then divided into three strata: shallow (< 20 m), medium (20 – 40 m), and deep (40 m- 60 m). Additionally, "Too deep" stratum (> 60 m) was created post-survey to include sites that were deeper than the expected depth of 60 m.

Fishing pressure was measured by cumulative boat hours estimated from VMS data provided from SFA. The VMS log under fishing operation was extracted by filtering logbook data between 7am to 5pm (fishing operation time) and traveling speed below 1 nautical mile hr^{-1} (speed during fishing). Coordinates of filtered logbook entries were then imported as point vectors into ArcGIS. Each point represented one boat-hour since VMS data were logged hourly. Cumulative boat hours were then calculated by summing these points from 2004 to 2011 and then divided them into three strata based on natural breaks.

The entire possible fishing area (delineated by the fishery reporting grid) was divided into 5 km grids and each grid cell was assigned to a survey stratum based on two factors, depth and fishing pressure (Table 2.1). Each stratum was then assigned twenty random survey points for each year, which was considered the maximum number of sites possible for a sampling period.

MPA survey sites were selected from the seven established protected areas within the sea cucumber fishing grounds. Each MPA was established for a different reason, and ranged in size from 86 to 1370 ha (Table 2.2). In order to test the efficacy of these MPAs for sea cucumber protection, we randomly allocated 10 transects each for inside and outside of MPA. Buffer zones of 500 m were created around each MPA using ArcGIS 10.0 to delineate the outside survey area (Fig. 2.2).

Survey method

Since survey sites were up to 60 m deep, we used two methods of underwater surveys due to diving safety constraints. At sites > 35 m, we used a remotely operated vehicle (ROV, VideoRay Pro 3 S [year 1], and Pro 3 GTO [year 2 and 3]) to survey 2 m wide by 120 m long transects using a clump weight system. For general sites that were < 35 m, paired divers conducted a 30 min timed swim using battery powered scooters with a transect width of 4 m. Average transect length for these scooter surveys was 519 m (± 213). For the MPA surveys, paired divers conducted 5 min timed swims, with an average transect length of 131 m (± 73). For dive surveys, a diver towed a buoy with GPS to calculate transect length.

For every sea cucumber found, all surveys recorded species identification, size, observed time, depth, and associated habitat. Sizes were measured to the nearest 1cm bin using a measuring tape. Associated habitat was recorded by taking percent benthic coverage that fell within 50 cm^2 square of each sea cucumber. Overall habitat of the transect was described at the end of the survey by estimating the amount of each habitat type along the transect. Habitats were divided into abiotic (sand, rubble, granitic boulder, and pavement) and biotic (macroalgae, soft coral, hard coral, sponge, and other).

ROV surveys could not record size of sea cucumbers until year three of the survey, when we mounted a Fuji FinePix REAL W1 F FX-3D 3DW camera that enabled stereo imaging. The 3D camera recorded each sea cucumber found on transects, and the imagery was analyzed using EventMeasure software (SeaGIS: http://www.seagis.com.au/) to obtain lengths. The camera was calibrated using CAL software (SeaGIS) before and after the survey to ensure accuracy of the size. Lastly, to compare ROV vs. SCUBA diver detectability, we surveyed eleven clump weight transects (later referred as “comparison transects”) using both ROV and divers, and compared sea cucumber counts between the two methods.

FAO data

With support from FAO, SFA conducted a baseline survey of sea cucumbers in 2004 (Aumeruddy et al. 2005). The 2004 survey covered the entire Mahe and Amirantes plateau and were stratified by depth, region, and habitat (Fig. 2.1B). Similar to our study, the survey collected count information for all species, as well as habitat data for each transect. Depth was grouped into three categories: shallow (< 20 m), intermediate (20-50 m), and deep (> 50 m). Region was classified as either, “central” or “perimeter” of the plateau.

Data Analysis

Accounting for the clumped distribution of sea cucumbers

Sea cucumbers were often found in aggregations resulting in a large number of zero values in our data. This high variability reflects natural ecological processes and needs to be considered

(Bolker 2008). To account for the clumpy distribution of our data, we used a negative binomial distribution for all of our non-mixed model analysis. For mixed models, we used a Poisson distribution with an observation-level random effect to account for the extra variability in these data. We could not use zero inflated distribution models since our sample size was too small to afford proper parameter estimation.

ROV and Dive Survey Method Comparison

To test for equal detection rates in ROV and diver surveys we used standardized major axis analysis (SMA) using the package "smatr" (Warton et al. 2012) for R 3.1.3 (R Core Team 2015). SMA treats variability in predictor and response variables equally, making it suitable for methods comparisons. A slope not significantly different from 1 means the two measurement methods agree (Warton et al. 2006). Instead of assuming no error in observations, it assumes both measurements have errors (Warton et al. 2002). We used the data from "comparison transects" to conduct SMA.

Additionally, to test if ROV and dive survey had the same encounter rates despite differences in survey area size, we looked at the effect of survey method on density while accounting for depth. We only used data from the medium depth strata since these were the only strata that used both survey methods (31 dive surveys and 20 ROV surveys). We used a generalized linear model (GLM) with "MASS" package for R (Venables & Ripley 2002) and assigned survey method and depth as the explanatory factors under a negative binomial distribution. The slope of the method factor in the GLM was used to standardize the ROV and dive data when there was a significance difference between the two survey methods.

Size and weight analysis

Sea cucumbers are known for their flexible body shape, making it difficult to obtain reliable length measurements (Laboy-neives et al. 2006). However, sea cucumber volume and weight stays constant regardless of the body shape change (Yamana and Hamano 2006). Therefore, we converted length and width into body weight using the equation of Prescott et al. (2015):

$$W = a*L^b*D^c$$

where W is weight (in gram), L is length (in cm), D is width, and a, b, and c are the coefficients for each species. We only were able to estimate the weight for *H. atra, A. miliaris, H. nobilis, H. fuscogilva, T. ananas, H. edulis, S. herrmanni, B. atra, P. graeffei,* and *S. choloronotus* since other species parameter was not available. Since they have similar characteristics, we used parameters for *H. whitmaei* to convert size of *H. nobilis* to weight, although *H. whitmaei* was recently identified as a different species from *H. nobilis* (Uthicke et al. 2004b). We created linear models for each species to estimate mean weight and test the effect of depth and fishing effort factors on sea cucumber weight using marginal likelihood tests.

Estimating density and stock size and identifying drivers

In order to estimate the density for each species, we first created generalized additive models (GAMs) using depth and fishing pressure at each transect as predictors. We created three models to predict the density for each species using the following predictors; 1) with just depth, 2) just fishing pressure, and 3) depth and fishing pressure. We then selected the best model for predicting stock size based on Akaike Information Criterion score corrected for small sample size (AICc), so as to prevent overfitting (Burnham and Anderson 2003). We also tested the significance of the predictors for estimating density using marginal likelihood tests on the full model (Table 2.3).

We estimated total stock size by creating a table with the combination of average depth and fishing pressure for the entire Seychelles fishing area divided into 5 km grids. We then estimated the density and standard error for each corresponding grid cell using the best fit model, and multiplied the estimated density with cell size to estimate the stock size for each grid cell. Lastly, we summed the estimated stock for each grid cell to calculate the total stock size (Table 2.3).

To estimate the overall density for each species, we divided the total stock size by the entire grid area (7,812,539 ha). To estimate the standard error of the total sock size, we conducted Monte Carlo simulation where we estimated total stock size 1000 times by drawing normal random variates for each grid cell using the predicted corresponding standard error and summing the predicted stock size. This in turn gave us the standard error distribution of the overall total stock size. We then divided the minimum and maximum standard error total stock size and divided this with total grid area size to estimate the standard error of the overall density estimates.

We further tested to see if there was a significant density difference between commercial and non-commercial species using a generalized additive mixed model (GAMM) using the R package 'gamm4' (Wood and Scheipl 2014). *A. miliaris, H. atra, H. fuscogilva, H. nobilis, Pentard, T. ananas* were categorized as "commercial" species, and *B. atra, B. marmorata, B. subrubra, H. fuscopunctata, H. edulis, H. lecanora, P. graeffei, S. choloronotus, S. herrmanni* were categorized as "non-commercial" species. Depth and fishing pressure were included in the model since they were assumed to contribute to differences in density. Counts were modeled with a Poisson distribution, with an observation-level random effect for overdispersion. Species was included as a random effect to account for unexplained differences between species for total mean density. We used a marginal likelihood test to compare the density difference between targeted and non-targeted species, as well as correlations with fishing pressure and depth.

Density Comparison Between FAO 2004 survey

In order to examine density changes over time, densities of commercial species from this study were compared with the FAO survey conducted in 2004 (Aumeeruddy et al. 2005). We created GAM that predicted density along a depth gradient using both the FAO data and the current study. We included a survey year factor to test for any difference in mean density between the two surveys using a marginal F-test.

Habitat Preference

To increase the encounter rate for sea cucumbers, we used long transects that averaged about 500 m each. However, this made it difficult for the transects to be conducted within a homogenous habitat. Therefore, we explored habitat preference of sea cucumbers in two spatial scales (small scale [1-10 m^{-2}] and large scale [100-1,000 m^{-2}]).

For small scale habitat analysis, we used the habitat recorded at the location of the animal. For large scale analysis, we used the overall transect habitat. We described the preferred small scale habitat of each species by using non-metric multidimensional scaling (NMDS) using the “vegan” package for R (Oksanen et al. 2007). NMDS maps observed response variable dissimilarities onto ordination space and can handle nonlinear responses of any shape (Oksanen et al. 2007). For small-scale habitat analysis, we used habitat coverage as our response variable and looked at the grouping of habitats, as well as species preference, to these habitat groups. Each transect was represented as a site and each species preference was delineated with 95% confidence interval ellipse in the ordination space.

For habitat preferences at the larger scale, we used canonical correspondence analysis (CCA) using the "vegan" package for R (Oksanen et al. 2007) to visualize and test each habitat's significance using a permutation procedure (Oksanen et al. 2007). CCA allowed us to extract major gradients among combination of habitats that explained the species distribution and tested the significance of individual habitat component using sequential significance test and marginal test.

Refugia Efficacy Tests

MPAs and deeper strata should have higher densities and larger sizes of sea cucumbers since fishers cannot access these areas. We tested these hypotheses by comparing the density and size of each commercial species among fished areas, MPAs, and deeper depth strata.

Deep refugia

To test if deeper waters act as refugia for commercially targeted sea cucumbers, we first selected our data to only contain commercial species. Secondly, we grouped our data collected > 40m as "deep refugia" and grouped the remaining data collected < 40 m as "accessible sites". We then created generalized linear mixed model (GLMM) that estimated mean density for each group accounting for over-dispersion and species variance using "lme4" package for R (Bates et al. 2014). Lastly we applied marginal likelihood ratio tests using the GLMM to test the deep refugia effect using the "lmtest" package for R (Zeileis and Hothorn 2002).

We compared sea cucumber weight between accessible sites and deep refugia sites by creating linear mixed models (LMM) using the package “lme4” for R (Bates et al. 2014). We set species as a random variable and set depth as a fixed effect. Effects of depth refugia were then tested by comparing a null model with the LMM using “lmerTest” package for R (Kuznetsova et al. 2015). Additionally, we used PCA in the “vegan” package for R (Oksanen et al. 2007) to detect habitat differences between deep refugia and divable areas.

MPA

To test MPA efficacy, we created GLMMs to examine density difference of commercially targeted species between inside and outside MPAs. We accounted for the difference of five MPAs and five species by setting both MPAs and species as random effects, and setting “inside or outside of MPAs” as a fixed effect. We also included Transect ID as random effect to account for the over-dispersion in Poisson distribution, and included depth as a fixed effect to account for the density difference caused by depth. We used likelihood ratio test to compare MPA efficacy using “lmerTest” package for R (Kuznetsova et al. 2015). Pentard was excluded from this analysis since it was only found twice during the survey.

We compared average weight difference of sea cucumbers between inside and outside of MPAs by building a LMM using “lme4” package for R (Bates et al. 2014). We set species as a random effects, as well as MPA ID and depth to account for factors that could influence the size difference of the animal. Weight differences between inside and outside of MPAs was tested by comparing the full model with null model using “lmerTest” package for R (Kuznetsova et al. 2015).

Lastly, we ran constrained analysis of principal coordinates (CAP) to visually examine species composition differences between inside and outside MPAs using the “vegan” package for R (Oksanen et al. 2015). CAP ordinates the dissimilarity matrix of communities, and use Euclidean distance in the ordination space as the response to see how well predictors explain multivariate variation (Anderson & Willis 2003). We set the following as predictors for CAP: In/Out of MPA, Depth, and MPA ID. We hypothesized that species composition would be different if commercially targeted species were less abundant outside of MPAs even while accounting for depth and MPA variances. We also tested this hypothesis with PERMANOVA using the adonis function in the "vegan" package for R (Oksanen et al. 2015).

Result

ROV and Dive Survey method comparison

Eleven paired transects containing four sub-transects each were used to compare the detection accuracy between the ROV surveys and underwater visual censuses. The slope and elevation showed no significant deviation from 1 ($p>0.05$), thus we concluded that both survey methods were equally good at detecting sea cucumbers within a transect.

We further tested if differences in survey area size caused significant difference in density, and found no significant differences between the density of sea cucumbers estimated by ROV survey and dive survey ($p=0.28$, $\chi^2=1.164$, d.f.=1).

Size and Weight Analysis

Using the model of Prescott (2015), we converted length and width of sea cucumbers to weight for *A. miliaris, H. atra, H. nobilis, H. fuscogilva, T. ananas, H. edulis, S. herrmanni, B. atra, P.*

graeffei, and *S. choloronotus* (Table 2.3). Four species showed significantly increased weight towards deeper habitats: *H. atra* ($p<0.01$), *A. miliaris* ($p=0.004$), *B. atra* ($p=0.05$), and *P. graeffei* ($p=0.01$). Although not significant, the remaining species also showed increasing body weight toward deeper sites, except for *H. nobilis* and *S. choloronotus*. *A. miliaris* and *B. atra* showed significant increases in weight with increasing fishing pressure ($p=0.01$, $p=0.05$ respectively). Although not significant, *H. nobilis* and *T. ananas* had noticeable lower weight as fishing pressure increased.

Environments affecting density and stock size estimate

A total of 356 transect sites (0.73 km^2) were surveyed between 2011 and 2013. When the actual survey site did not match the assigned survey strata, it was re-categorized to the new corresponding strata. A total of 25 species of sea cucumbers, including three unidentified species and two undescribed species, were found during the survey (*Actinopyga echinitis, A. mauritiana, A. miliaris, A. spp, Thelenota anax, T. ananas, Bohadschia atra, B. marmorata, B. subrubra, B. spp, Holothuria fuscopunctata, H. atra, H. edulis, H. fuscogilva, H. isuga, H. lecanora, H. nobilis, H. scabra, H. spp, Pearsonothuria graeffei, Stichopus choloronotus, S. herrmanni, S. horrens,* Pentard (undescribed), and yellow surf-fish(undescribed)). Among these species, *A. echinitis*, *A. mauritiana*, *A. spp*, *T. anax*, *B. spp*, *H. isuga*, *H. spp*, *S. horrens*, and yellow surf-fish were considered too low in abundance, and thus excluded from analysis.

All GAMs showed gently sloped unimodal relationship with both depth and fishing pressure gradients. The best fit model explained, on average, 44% of the variance of these data (Table 2.4). Depth was a significant predictor for all species except *T. ananas* and *H. nobilis*, indicating that most species have a preferred depth (Table 2.4). Fishing pressure was only a significant factor for *B. subrubra*, *H. atra*, and *S. choloronotus* (Table 2.4).

The most abundant sea cucumber species in the Seychelles was *B. marmorata* with more than 56 million (±2 million) individuals estimated to be present among the water of Seychelles. *A. miliaris* was the most abundant among commercially targeted species, which was 6th in overall species abundance. The least abundant species were B. *atra*, *H. edulis*, and *P. graeffei*. These were all non-targeted species, but most of them preferred shallow areas, restricting their range and making them have low abundance when calculated for overall plateau.

When we compared the differences in mean density between commercially targeted species and non-commercial species, we found no significant difference between the two species groups (p=0.39). Although not significant, the commercial species group showed lower density at greater depths compared to non-commercial species (p=0.88) (Fig. 2.3).

Density Comparison Between FAO 2004 survey

Density of *H. atra* and *H. nobilis* declined significantly from FAO survey in 2004 to this study conducted from 2011 to 2013 (Table 2.5). *A. miliaris* showed a significant increase from 2004 to 2011. *H. fuscogilva*, Pentard, and *T. ananas* showed no significant change between the two survey years (Table 2.5).

Habitat Preference

NMDS plot for small scale habitat showed a grouping explained by the presence of shallow biotic cover (e.g., seagrass, sponges, hard and algae), deeper area with limited biotic habitat dominated by sand and rubble, hard bottom (pavement) with hard coral, and area with boulders

(Fig. 2.4). Ellipses delineating the 95% confidence interval showed Pentard and *A. echinitis* residing at different habitat than the other species. Pentard were most often found associated with soft bottoms with biotic cover (soft coral, sea grass, and algae), while *A. echinitis* were most often found near hard bottom habitat with hard coral. Additionally, *H. edulis, S. chloronotus,* and *P. graeffei* showed similar habitat preference residing near hard bottom habitats as well, but not influenced by the presence of hard coral. All commercial species except Pentard resided in a mixed habitat with sand and rubble rather than hard bottom.

For large scale habitat analysis, 25% of the total inertia of CCA was explained by habitat. Rubble habitat was excluded from the analysis since the loading showed redundancy with hard coral. The first CCA axis showed a gradient of depth from deep to shallow habitats, which were dominated by pavement and algae (Fig. 2.5). The order of the species found along the depth gradients from shallow to deep were: *H. atra, A. echinitis, S. chloronotus, P. graeffei, B. atra, T. ananas, H. nobilis, H. fuscopunctata, B. subrubra, A. miliaris, H. edulis, H. fuscogilva, S. herrmanni, B. marmorata, Pentard,* and *H. lecanora* (Fig. 2.5). Similar to the small-scale habitat analysis, the second CCA axis was explained by substrate types, with boulder and hard coral (hard bottom) along the bottom of the axis, and sand and sea grass towards the top. However, sand and sea grass were influenced by depth (first axis) resulting in two distinct species group. *H. atra* were often found around the area dominated by shallower sea grass habitat, whereas *B. marmorata* and Pentard were found more often at deeper sandy area. Hard bottom sites were dominated by *P. graeffei, T. ananas,* and *H. nobilis*, which were observed often on transects with corals.

Sequential significance test based on permutation for each environmental terms showed that depth, sand, sea grass, hard coral (or rubble), pavement, and boulder had significance influence on sea cucumber habitat preferences. However, when we conducted the marginal test, depth was the only habitat that had a significant effect on habitat preference ($p=0.001$). Lastly, it is important to note that we only examined adult habitat affinities as we did not observe any juvenile sea cucumbers (< 15 cm) during our surveys, and their associated habitats are likely very different from those of the adults.

Refugia Efficacy Tests

Deep refugia

Contrary to theory, commercially targeted sea cucumbers showed significantly higher densities in shallower depth strata, which were more accessible to fishers ($p<0.01$) (Fig. 2.6). This is likely due to the habitat shift that occurs from shallow and divable sites to deeper and non-divable sites (Fig. 2.7). The shallower sites contained a wide variety of habitats and biotic cover, whereas 89% of the habitat surveyed in deeper sites were 100% sandy bottom. Any presence of biota above 1% decreased significantly as depth increased ($p=0.004$). This could strongly influence the organic matter available for sea cucumbers and thus limit their density even though there were minimal fishing pressure. Conversely, individual sea cucumber weight was 152% larger in deep refugia sites compared with shallow accessible sites ($p<0.01$).

MPA

Five of seven MPAs were examined for their effect on protecting commercially targeted sea cucumber species (Fig. 2.2). Sampling sites were randomly placed, but we noted that habitats were similar both inside and outside of the MPAs, except for Baie Turney and Port Launay. Data were not collected outside of Baie Turney and Port Launay since similar habitat areas with each MPA was not found within the 500m buffer.

A test of MPA efficacy using GLMM did not detect any significant density differences for commercial species between inside and outside of MPAs (p=0.70) (Fig. 2.8). This was not surprising since most MPAs were set to protect coral reefs, which is not the preferred habitat for sea cucumbers. Based on CAP, sea cucumber assemblage structure inside MPAs was a subset of the assemblage outside (Fig. 2.9). PERMANOVA showed that assemblage differences were significantly driven by depth (p=0.03) and not by inside/outside of MPAs (p=0.56). This indicates that there were no significant differences between the ratio of commercially targeted species and non-targeted species between inside and outside of the MPAs. Additionally, mean weight of each sea cucumber species was not significantly different between inside and outside of the MPA (p=0.4).

Discussion

General findings

Fishery-independent surveys improve the reliability of stock assessments, and indispensable components of any modern stock assessment program (Gunderson 1993). It also helps inform sustainable fishery management under an EBFM framework through testing ecological hypotheses such as evaluating the impact of habitat degradation on populations.

Our fishery-independent survey provided information on stock abundance, size, *in situ* abundance trends, preferred habitats, and effects of refugia. Although overfished stocks often show low density with high fishing pressure (Jennings and Lock 1996), our study showed that habitat (especially depth) was the main driver of sea cucumber density in the Seychelles, rather than fishing pressure. This was clear when we compared species' densities between sites that were accessible and inaccessible to fishers. Most of the species did not show significant differences between fished and unfished area.

Commercial species should be less abundant (in the sense of total population size) than the non-commercial species if fishing is the main driver of abundance. Instead, our survey showed that commercial species were as abundant as the non-commercial species, which could be due to the proportion of different habitats and depth strata across the plateau. Half of the commercial species preferred deeper habitats, which accounted for much of the area of the plateau. Conversely, some of the non-targeted species had the lowest abundances since they were restricted to shallow areas (<20m) that only accounted for 38 % of the total plateau. It is important to note though, that this is the current abundance, and we are not talking about previous abundance. The commercial species could have been significantly more abundant than non-commercial species previously, and now have declined to similar abundance.

When we looked at trends in abundance, we saw *H. atra* and *H. nobilis* had declined in number from the 2004 FAO survey to this study conducted from 2011 to 2013. In addition, catch per unit effort (CPUE) from fishery logbooks showed a significant decline for *H. nobilis* as well (Koike et al., *in prep*). Unlike other species, larger *H. nobilis* were more abundant in shallower area, making them easier to harvest. A study from Australia showed that *H. nobilis* did not recover from over exploitation, due to slow maturity and low recruitment (Uthicke et al. 2004a). The results above show that *H. nobilis* is especially vulnerable to fishing pressure compared to other sea cucumber species. Conversely, *A. miliaris* showed a significant increase in stock size from the 2004 FAO survey to the current survey. Interestingly, *A. miliaris* showed a significant decline in CPUE, suggesting that the decline in CPUE is not due to ecological factors but possibly socio-economic ones. The large decline in *H. atra* is also interesting since it has only been fished for only two years prior to our survey. Furthermore, this species has also been fished in Pacific countries, but has been reported to maintain its density possibly due to lower fishing pressure and asexual reproduction (Friedman et al. 2011), thus making Seychelles' case unique.

Juvenile sea cucumbers are frequently found in shallow sea grass habitats and migrate to deeper area where growth plateaus (Conand 1993, Ramofafia et al. 2000). Consistent with this was our finding that weight for most species increased with depth, although not significantly. Body weight also increased with increasing fishing pressure for most species. This was unexpected since overfishing usually leads to a decrease in the mean size of individuals (Anderson 2011, Eriksson 2015). Our study suggests the following: 1) stocks have not been depleted to the point where large individuals are noticeably depleted, 2) fishers fish the optimum habitats where large-bodied animals prefer, or 3) a combination of both.

Substrate type (hard bottom or soft bottom) strongly influenced the species composition of sea cucumbers regardless of scale. Depth at the large scale, and biota in small scale were important for explaining species composition. Since marginal test is known to be conservative for CAP, we also believe sea grass, hard coral (or rubble), pavement, and boulder still are an important factor for sea cucumber species composition and abundance. Since fishers harvest whatever species they see, it is important to know which sea cucumber species will likely be found together. At large scales, *H. fuscogilva*, *Pentard* and *A. miliaris* show similar habitat affinities, with the highest densities in sandy bottom habitats that were in relatively deeper water with some soft corals. *H. nobilis* and *T. ananas* showed similar habitat associations, with both being found in higher abundance in boulder and hard coral habitats. *H. atra* preferred shallow areas with sea grass and algae coverage which was different from all other commercial species. This indicates the possibility of large shifts in fishing ground when fishers change their target species.

The Seychelles have well established MPAs, but our study showed that none were effective for protecting commercial sea cucumbers. Both abundance and size showed no significant difference between inside and outside of MPAs. Species composition of sea cucumbers also showed similarity between inside and outside MPAs, indicating absence of selective fishing pressure. This could be because most MPAs in the Seychelles were established to conserve reef biodiversity rather than sea cucumbers. In fact, MPAs were significantly shallower (15m) than the average depth of the Mahe Plateau (37m). Hard coral cover was also significantly higher (11%) in MPAs compared to the plateau (mean = 5%). We also found that habitat within MPAs is not the preferred habitat for most commercially targeted species. *H. nobilis* and *T. ananas* do show preference to hard coral, but they tend to be found in deeper sites with some sandy patches or hard pavement for them to attach on.

Deeper sites are thought to be a refuge for sea cucumbers since they are beyond the safe operating depths for most Seychelles fishing operations. However, our study showed the opposite, with shallower accessible sites having higher densities than the deeper sites. We suspect this was because non-divable habitat was dominated by sand without any biotic cover. Sea cucumbers are known for their site affinity toward higher organic matters (Slater and Carton 2010). Therefore, we believe sea cucumbers avoid deep areas without biota cover since it offers considerably less available organic matter despite the absence of fishing pressure. However, although very few in number, individuals found at deeper sites were significantly larger in size. This agrees with the findings in Solomon Islands (Mercier et al. 2000) and Australia (Uthicke and Benzie 1999), suggesting shallower habitat function as nursery and mature individuals migrating to deeper habitat.

Incorporating Fishery Independent Survey Data to Fishery Management

Estimates of abundance for fish populations have always been required for fisheries management purposes. Traditionally, abundance indicator was estimated using CPUE calculated from catch records (Quinn and Deriso 1999). However, the use of CPUE alone has declined over the years due to: unrealistic assumption that do not consider hyper/hypo stability of the stock; development of VPA which does not rely on CPUE trends; and technical complications such as gear difference between fishing fleets (Gunderson 1993). Fishery-independent survey data has become a strong complement to fishery-dependent data, since it allows 1) less biased stock size estimate, 2) test management assumptions (such as protection efficacy, 3) evaluate the relative importance of environmental influences (such as habitat degradation, pollution, and developments) and 4) give us insight to inter/intra specific interactions that regulate population size. The data can be collected through various methods such as trawl surveys, acoustic surveys, egg and larval surveys, direct counts, and tagging. Underwater visual survey is popular in tropical reef area since the surveyors often have to collect multi-species/multi-trophic data and rugose terrain interfere with trawling methods. Here, we list several practical uses of our survey information for the management of the Seychelles sea cucumber fishery.

Our underwater visual survey has allowed an accurate estimate of stock size for each sea cucumber species in Seychelles. This information can be used for calculating reliable catch limits, because catch limits are calculated by multiplying stock size and some estimate of fishing mortality. Additionally, in situ surveys over time can provide an independent estimate of abundance trends that does not have the same biases associated with fishery-dependent surveys (e.g., changes in fishing power, under and/or over-reporting, selective fishing sites, and other nonrandom factors). The temporal abundance trend is necessary to fit production type stock assessment models and having more than one data source to verify the trend will greatly improve the quality of the model.

In situ surveys are also great to test management assumptions and animal behavior assumptions. Some fishers believed that there were deep water refugia for sea cucumbers that were not being fished and they were therefore opposed to new management regulations. Our results clearly showed that there is no depth refuge for sea cucumbers in the Seychelles, which should help inform stakeholder involvement in the management process.

Species interaction sometime is a key to stock growth. Interspecific competition can sometime stump the recovery of a stock that is under pressure (Magnan et al 2005). Furthermore, fishermen could selectively target one species over another which could change the natural dynamic of species interaction. Our study identified species that share the same habitat, and managers can investigate further specific species interactions in the future.

Habitat information is key to understanding species distribution and spatial growth rate differences. Degraded habitat can often decrease the available resources/protection for stock to grow. Our dive survey delineated habitat patterns around Seychelles waters, and identified degraded sea cucumber habitats due to land fill and other developments. We further noted the spatial structure in body size. This information could then be used in EBFM decisions and used to create spatially explicit stock assessment models.

Lastly, although not conducted in this study, we recommend conducting egg/larval survey for sea cucumbers. Sea cucumber juveniles are known to be cryptic and they were only detected twice during our surveys. Sea cucumbers are thought to spawn infrequently (Purcell 2010) but understanding their recruitment frequency is critical in fishery management. Therefore, conducting long term monitoring of larvae (through use of plankton net or light traps) would be a great additional fishery independent survey to be conducted.

With recent improvement in computer power, we are now able to create a stock assessment model in Bayesian framework that can refer to both fishery independent survey data and fishery dependent log data under one model. This allows much better estimate of population dynamic parameters since bias from direct survey of abundance could be verified from independent source of data. We can also add habitat specific information in the model so that spatial variance is accounted. Furthermore, by creating such spatially explicit models, we can include ecological information and simulate spatial closure effects using data collected from fishery independent surveys. Having a stock assessment model that allows simulations is critical for successful management since managers can simulate the proposed regulation outcomes to stakeholders for a transparent discussion of management outcomes (Walters and Martell 2004). Our study demonstrates the importance of ecological knowledge and hypotheses testing based on fishery independent surveys and possibility for further incorporation into stock assessment.

References

Anderson, S.C., Flemming, J.M., Watson, R. and Lotze, H.K., 2011. Serial exploitation of global sea cucumber fisheries. *Fish and Fisheries*, 12(3), pp.317-339.

Anderson, M.J. and Willis, T.J., 2003. Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. *Ecology*, 84(2), pp.511-525.

Aumeeruddy, R. and Conand, C. (2007). Seychelles' sea cucumber fishery: Data on processed products and other parameters. *SPC Beche de Mer Information Bulletin*, 26, August 2007.

Aumeeruddy, R. and Payet, R. (2004). Management of the Seychelles sea cucumber fishery: status and prospects. *Advances in Sea Cucumber Aquaculture and Management*. FAO Fisheries and Aquaculture Technical Paper. No. 463. Rome, FAO.

Aumeeruddy, R., & Skewes, T. (2005). Resource assessment of the holothurian populations in the Seychelles. *SPC Beche-de-mer Information Bulletin*, 21, 19-21.

Aumeeruddy R, Skewes T, Dorizo J, Carocci F, Coeur de Lion F, Harris A, Henriette C, Cedras M. (2005). *Resource assessment and management of the Seychelles sea cucumber fishery*. FAO Project Number: TCP/Seychelles/2902(A), November, 49.

Aumeeruddy, Rodney Quatre, and Nicholas VC Polunin. (2013). Sea cucumbers in the Seychelles: effects of marine protected areas on high- value species. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 23, 3, 418-428.

Bates D, Maechler M, Bolker B and Walker S. (2014). *lme4: Linear mixed-effects models using Eigen and S4*. R package version 1.1-7, <URL:http://CRAN.R-project.org/package=lme4>.

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., ... &

Weatherall, P. (2009). Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. *Marine Geodesy*, *32*(4), 355-371.

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. *Fish. Invest.*, Ser. II., 19, 533.

Bolker, B.M., 2008. *Ecological models and data in R*. Princeton University Press.

Brodziak, J. and Link, J., 2002. Ecosystem-based fishery management: what is it and how can we do it? *Bulletin of Marine Science*, 70(2), 589-611.

Burnham, Kenneth P., and David Anderson. (2003). *Model selection and multi-model inference. A Pratical informatio-theoric approch.* Springer.

Cariglia, N., Wilson, S.K., Graham, N.A., Fisher, R., Robinson, J., Aumeeruddy, R., Quatre, R. and Polunin, N.V. (2013). Sea cucumbers in the Seychelles: effects of marine protected areas on high- value species. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 23(3), 418-428.

Conand, C. (1993). Reproductive biology of the holothurians from the major communities of the New Caledonian Lagoon. *Marine Biology*, 116(3), 439-450.

Crowder, Larry, and Elliott Norse. (2008). Essential ecological insights for marine ecosystem-based management and marine spatial planning. *Marine Policy*, 32, 5, 772-778.

Domingue, Gerard, Rolph Payet, and Nirmal Jivan Shah. (2001). *Marine Protected Areas in the republic of Seychelles*.

Eriksson, H. and Byrne, M. (2015). The sea cucumber fishery in Australia's Great Barrier Reef Marine Park follows global patterns of serial exploitation. *Fish and Fisheries*, 16(2), 329-341.

Friedman, K., Eriksson, H., Tardy, E., & Pakoa, K. (2011). Management of sea cucumber stocks: patterns of vulnerability and recovery of sea cucumber stocks impacted by fishing. *Fish and Fisheries*, *12*(1), 75-93.

Gaines, S.D., White, C., Carr, M.H. and Palumbi, S.R. (2010). Designing marine reserve networks for both conservation and fisheries management. *Proceedings of the National Academy of Sciences*, 107(43), 18286-18293.

Gabriel, W.L., Sissenwine, M.P. and Overholtz, W.J. (1989). Analysis of spawning stock biomass per recruit: an example for Georges Bank haddock. *North American Journal of Fisheries Management*, 9(4), 383-391.

Gunderson, Donald R. (1993). *Surveys of fisheries resources*. John Wiley & Sons.

Haddon, M. (2010). *Modelling and quantitative methods in fisheries*. CRC press.

Halpern, B.S., Lester, S.E. and McLeod, K.L. (2010). Placing marine protected areas onto the ecosystem-based management seascape. *Proceedings of the National Academy of Sciences*, 107(43), 18312-18317.

Hilborn, R. and Walters, C.J. (1992). Quantitative fisheries stock assessment: choice, dynamics and uncertainty. *Reviews in Fish Biology and Fisheries*, 2(2), 177-178.

Jari Oksanen, F. Guillaume Blanchet, Roeland Kindt, Pierre Legendre, Peter R. Minchin, R. B. O'Hara, Gavin L. Simpson, Peter Solymos, M. Henry H. Stevens and Helene Wagner (2015). *vegan: Community Ecology Package*. R package version 2.3-0. <http://CRAN.R-project.org/package=vegan>

Jennings, S. and Lock, J.M. (1996). Population and ecosystem effects of reef fishing. *In Reef Fisheries*, 193-218.

Johnson, A.E., Cinner, J.E., Hardt, M.J., Jacquet, J., McClanahan, T.R., and Danchirico,J.N. (2013). Trends, current understanding and future research priorities for artisanal coral reef fisheries research. *Fish and Fisheries*. 14, 281–292.

Koike, H., A. Friedlander, J. Brodziak, C. Gerry, K. Edwards. (In prep). Chapter 2. Thesis.

Kuznetsova, A,. Per Bruun Brockhoff and Rune Haubo Bojesen Christensen (2015). *lmerTest: Tests in Linear Mixed Effects Models*. R package version 2.0-29. <http://CRAN.R-project.org/package=lmerTest>

Laboy-nieves, E. N., and Conde, J. E. (2006). A new approach for measuring Holothuria mexicana and Isostichopus badionotus for stock assessments. *SPC Beche-de-mer Information Bulletin* 24, 39–44.

Levin, S.A. and Goodyear, C.P. (1980). Analysis of an age-structured fishery model. *Journal of Mathematical Biology*, 9(3), 245-274.

Magnan, P., Proulx, R., & Plante, M. (2005). Integrating the effects of fish exploitation and interspecific competition into current life history theories: an example with lacustrine brook trout (Salvelinus fontinalis) populations. *Canadian Journal Of Fisheries & Aquatic Sciences*, 62(4), 747-757.

Mercier, Annie, Stephen C. Battaglene, and Jean-François Hamel. (2000). "Periodic movement, recruitment and size-related distribution of the sea cucumber Holothuria scabra in Solomon Islands". *In Island, Ocean and Deep-Sea Biology*, pp. 81-100. Springer Netherlands.

Meyer, R. and Millar, R.B. (1999). BUGS in Bayesian stock assessments. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(6), 1078-1087.

Nowlis, J.S. and Friedlander, A. (2005). *Marine reserve function and design for fisheries management*. Island Press.

Oksanen, J., Kindt, R., Legendre, P., O'Hara, B., Stevens, M.H.H., Oksanen, M.J. and Suggests, M.A.S.S. (2007). The vegan package. *Community ecology package*, 631-637.

Pella, J. J. and P. K. Tomlinson. (2002). A generalized stock production model. *IATTC Bull.* 13, 10, 421-458.

Pikitch, E., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P.A.O., Doukakis, P., Fluharty, D., Heneman, B. and Houde, E.D. (2004). Ecosystem-based fishery management. *Science*, 305(5682), 346-347.

Prescott, J., Zhou, S. and Prasetyo, A.P. (2015). Soft bodies make estimation hard: correlations among body dimensions and weights of multiple species of sea cucumbers. *Marine and Freshwater Research*, 66(10), 857-865.

Prince, J., Hordyk, A., Valencia, S.R., Loneragan, N. and Sainsbury, K. (2015). Revisiting the concept of Beverton–Holt life-history invariants with the aim of informing data-poor fisheries assessment. ICES Journal of Marine Science: *Journal du Conseil*, 72(1), 194-203.

Purcell, S. W. (2010). *Managing sea cucumber fisheries with an ecosystem approach*. FAO.

Purcell, S.W., Mercier, A., Conand, C., Hamel, J.F., Toral- Granda, M.V., Lovatelli, A. and Uthicke, S. (2013). Sea cucumber fisheries: global analysis of stocks, management measures and drivers of overfishing. *Fish and Fisheries*, 14(1), 34-59.

Quinn, Terrance J., and Richard B. Deriso. (1999). *Quantitative fish dynamics*. Oxford University Press.

R Core Team (2015). R: *A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>

Ramofafia, C., Battaglene, S.C., Bell, J.D. and Byrne, M., (2000). Reproductive biology of the commercial sea cucumber Holothuria fuscogilva in the Solomon Islands. *Marine Biology*, 136(6), 1045-1056.

Richmond, R. H. (ed) (1996). *Suggestions for the Management of Sea Cucumber Resources in Micronesia*. Technical Report 101, University of Guam Marine Laboratory, November.

Simon Wood and Fabian Scheipl (2014). *gamm4: Generalized additive mixed models using* *mgcv and lme4*. R package version 0.2-3. <http://CRAN.R-project.org/package=gamm4>

Slater, M. J. and Carton, A. G. (2010), Sea cucumber habitat differentiation and site retention as determined by intraspecific stable isotope variation. *Aquaculture Research*, 41.

Toral-Granda, V., Lovatelli, A., Vasconcellos, M., Conand, C., Hamel, J. F., Mercier, A., ... & Uthicke, S. (2008). Sea cucumbers. A global review on fishery and trade. *SPC Beche de Mer Information Bulletin, 28,* 4-6.

Uthicke S, Welch D, and Benzie, J.A.H. (2004a). Slow growth and lack of recovery in overfished holothurians on the Great Barrier Reef: evidence from DNA fingerprints and repeated large-scale surveys. *Conserv Biol,* 18, 1395–404.

Uthicke, S., O'Hara, T. D., and Byrne, M. (2004b). Species composition and molecular phylogeny of the Indo-Pacific teatfish (Echinodermata : Holothuroidea) bêche-de-mer fishery. *Marine and Freshwater Research*, 55, 837–848.

Venables, W. N. and Ripley, B. D. (2002) *Modern Applied Statistics with S*. Fourth Edition. Springer, New York. (MASS package)

Walters, C.J. and Martell, S.J. (2004). *Fisheries ecology and management*. Princeton University Press.

Warton, David I., Duursma, Remko A., Falster, Daniel S., and Taskinen, S. (2012). smatr 3 - an R package for estimation and inference about allometric lines. *Methods in Ecology and Evolution*, 3(2), 257-259.

Warton D. I. and Weber N. C. (2002) Common slope tests for bivariate structural relationships. *Biometrical Journal*, 44, 161–174.

Warton D. I., Wright I. J., Falster D. S. and Westoby M. (2006) A review of bivariate line-fitting methods for allometry. *Biological Reviews,* 81, 259–291.

Yamana, Y. and Hamano, T. (2006). New size measurement for the Japanese sea cucumber

Apostichopus japonicus (Stichopodidae) estimated from the body length and body breadth. *Fisheries Science*, 72(3), 585-589.

Zeileis, A. and Hothorn, T. (2002). Diagnostic Checking in Regression Relationships. *R News* 2(3), 7-10. <http://CRAN.R-project.org/doc/Rnews/> (LMtest)

Table 2.1. Survey strata used for fishery independent survey conducted from 2011 to 2013. The strata were based on fishing intensity (measured in boat-hours) and depth.

	Light Fishing (<2 boat-hours)	Moderate Fishing (3 ~ 6 boat-hours)	Intense Fishing (> 7 boat-hours)
Shallow (< 20 m)	Shallow_Light	Shallow_Moderate	Shallow_Intense
Medium (20 m – 40m)	Medium_Light	Medium_Moderate	Medium_Intense
Deep (40 m -60 m)	Deep_Light	Deep_Moderate	Deep_Intense
Too Deep (> 60 m)	Too Deep_Light	Too Deep_Moderate	Too Deep_Intense

Table 2.2. Details of each MPA established within the Seychelles sea cucumber fishing ground.

Name	Size (ha)	Year established
Aride Marine Park	95.53	1979
Cousin Marine Park	158.16	1975
Ile Coco Marine National Park	165.48	1997
Curieuse Marine National Park	1370	1979
Ste. Anne National Marine Park	996.04	1973
Port Launay Marine National Park	154.26	1979
Baie Ternay Marine National Park	86.28	1979
Silhouette Marine National Park	143.77	1987

Table 2.3. Mean weight of sea cucumbers found in gram with sample size (n) and standard deviation (sd). Relationship between weight, depth, and fishing pressure was tested in linear model. Significance and effect size of the predictors are shown. Depth was based on SRTM30_PLUS bathymetry data (Becker et al. 2009). Fishing pressure was based on the boat-hours calculated from VMS data.

Species	*n*	Weight (g)	*sd*	Depth (g/m)	*p*	Fishing pressure (g/boat-hour)	*p*
Actinopyga miliaris	77	1925	1083	49.9	***0.004***	31.5	***0.01***
Bohadschia atra	94	2283	1048	61.8	***0.05***	47.6	***0.05***
Holothuria atra	157	1022	1360	29.6	***<0.01***	3.5	*0.73*
H. edulis	71	1571	1120	21.2	*0.25*	36.6	*0.13*
H. nobilis	22	2512	1563	-20.2	*0.69*	-52.6	*0.28*
H. fuscogilva	33	4250	2126	5.3	*0.92*	23.6	*0.21*
Personothuria graeffei	76	1153	1057	93.9	***0.01***	-3.0	*0.88*
Stichopus herrmanni	60	2511	1356	10.5	*0.71*	48.3	*0.4*
S. choloronotus	143	265	238	-6.7	*0.24*	2.8	*0.6*
Thelenota ananas	89	5208	2771	39.5	*0.46*	-21.8	*0.4*

Table 2.4. Summary of density, stock size estimated for each species within Seychelles waters. 'Environmental predictors' show p-values from a marginal F-test for depth and fishing effort (FE). 'Model' describes the best fit model used for estimating density (numbers in parentheses show the variance explained by the predictors). 'Density' and 'total stock size' shows the overall density and stock size estimated with standard error.

	Species	Env. Predictor		Model		Density (No. ha^{-1})	Total Stock Size (No.)
		Depth	FE	Type	%		
Commercial	*Actinopyga miliaris*	<0.01	0.59	Depth Only	42.6	1.04 (0.98 – 1.11)	8,145,737 (7,687,670 – 8,686,089)
	Holothuria atra	<0.01	0.04	Full	65.0	0.53 (0.45 - 0.61)	4,146,355 (3,523,207 – 4,751,389)
	H. fuscogilva	0.07	0.20	Full	32.6	0.29 (0.27 - 0.32)	2,262,371 (2,088,005 – 2,468,383)
	H. nobilis	0.53	0.12	FE Only	43.0	0.53 (0.52 - 0.54)	4,131,742 (4,033,332 – 4,237,351)
	Pentard	<0.01	0.15	Depth Only	34.8	0.18 (0.16 - 0.20)	1,402,414 (1,250,354 – 1,579,211)
	Thelenota ananas	0.11	0.10	Full	63.4	0.27 (0.24 - 0.30)	2,107,384 (1,891,591 – 2,347,228)
Non-commercial	*B. atra*	<0.01	0.14	Full	51.3	0.20 (0.15 – 0.25)	1,524,968 (1,199,680 – 1,956,768)
	B. marmorata	<0.01	0.20	Depth Only	39.4	7.27 (7.04 – 7.49)	56,777,069 (54,985,675 – 58,534,510)
	B. subrubra	0.04	0.04	Full	41.7	0.73 (0.62 – 0.84)	5,711,159 (4,861,560 – 6,526,817)
	H. fuscopunctata	<0.01	0.08	Full	51.3	1.30 (1.23 – 1.42)	10,142,395 (9,596,910 – 11,075,276)
	H. edulis	<0.01	0.15	Depth Only	37.2	0.11 (1.16 – 1.35)	9,886,630 (9,082,841 – 10,509,491)
	H. lecanora	<0.01	0.67	Depth Only	14.8	1.77 (1.67 – 1.87)	13,796,834 (13,027,616 – 14,590,681)
	P. graeffei	0.01	0.11	Depth Only	54.8	0.14 (0.12 – 0.16)	1,101,817 (946,586 – 1,217,556)
	S. choloronotus	0.11	0.01	Full	63.7	0.24	1,880,425

					(0.20 – 0.28)	(1,562,508 – 2,184,305)
S. herrmanni	<0.01	0.05	Full	52.7	1.20	9,396,888
					(1.11 – 1.32)	(8,688,490 – 10,345,420)

Table 2.5. Overall density estimated for FAO survey and UH survey in no. ha^{-1}. Density was estimated by dividing the predicted total stock size by the total area size used for prediction. Difference between the two survey years was tested using GAM and reported in *p*-value.

Species	FAO (2004)	UH (2011 - 2013)	*p*
Actinopyga miliaris	0.91	1.04	**<0.01**
Holothuria atra	4.03	0.53	**<0.01**
H. fuscogilva	0.35	0.29	0.17
H. nobilis	0.89	0.53	**<0.01**
Pentard	0.22	0.18	0.18
Thelenota ananas	0.22	0.27	0.46

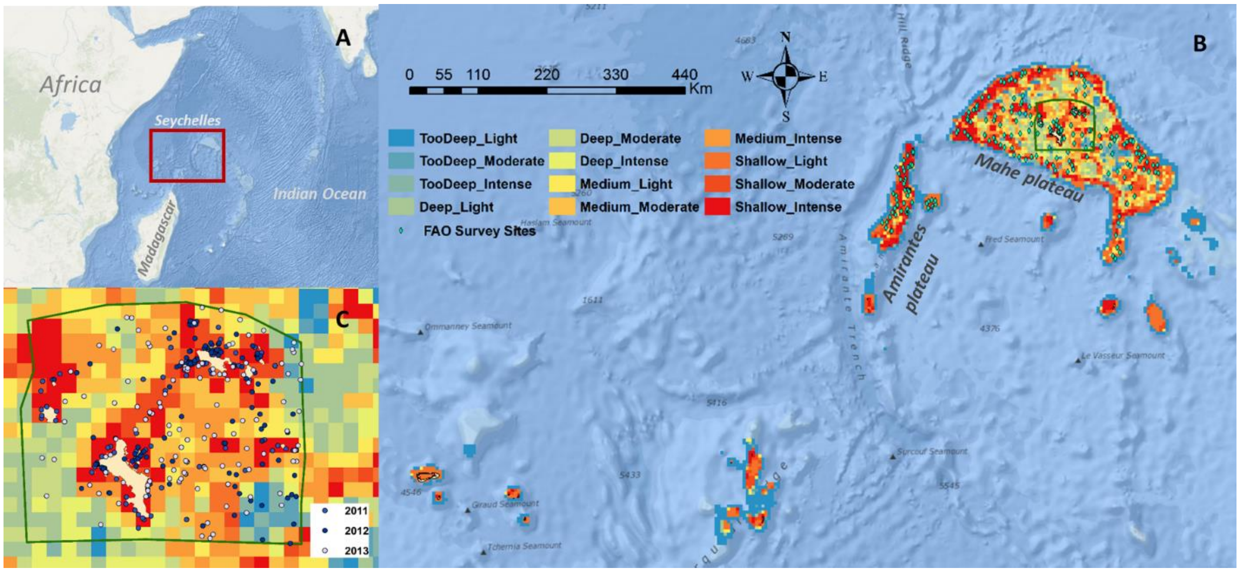


Figure 2.1. Map of study site. (A) Area of fishing ground delineated in red box. (B) Survey strata map for the entire fishing area. FAO survey sites conducted in 2004 are depicted in green dots. Area delineated in dark green is the survey area for this study. (C) Survey sites for this study color coded for each year. Green box is the survey area boundary.

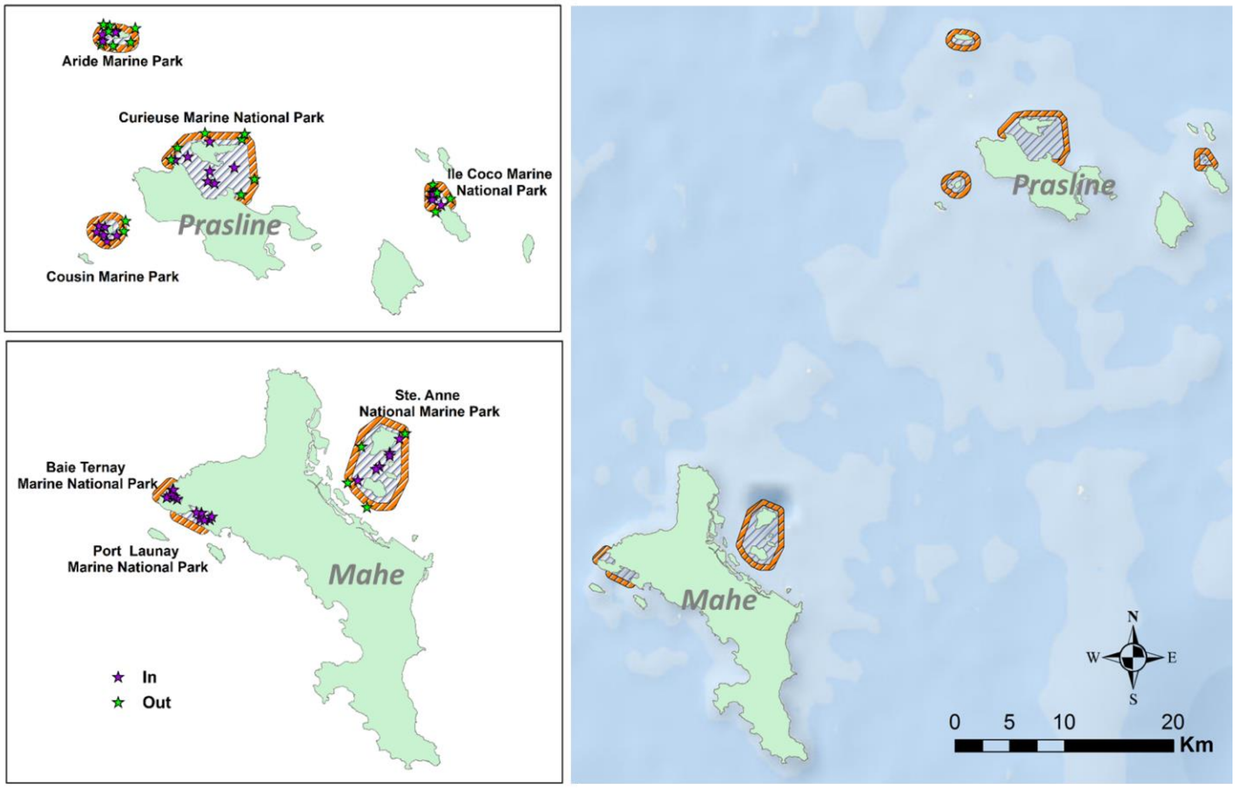


Figure 2.2. MPA sites surveyed around Prasline and Mahe. Blue shaded areas are MPAs and areas in orange are 500 m buffers outside of MPAs.

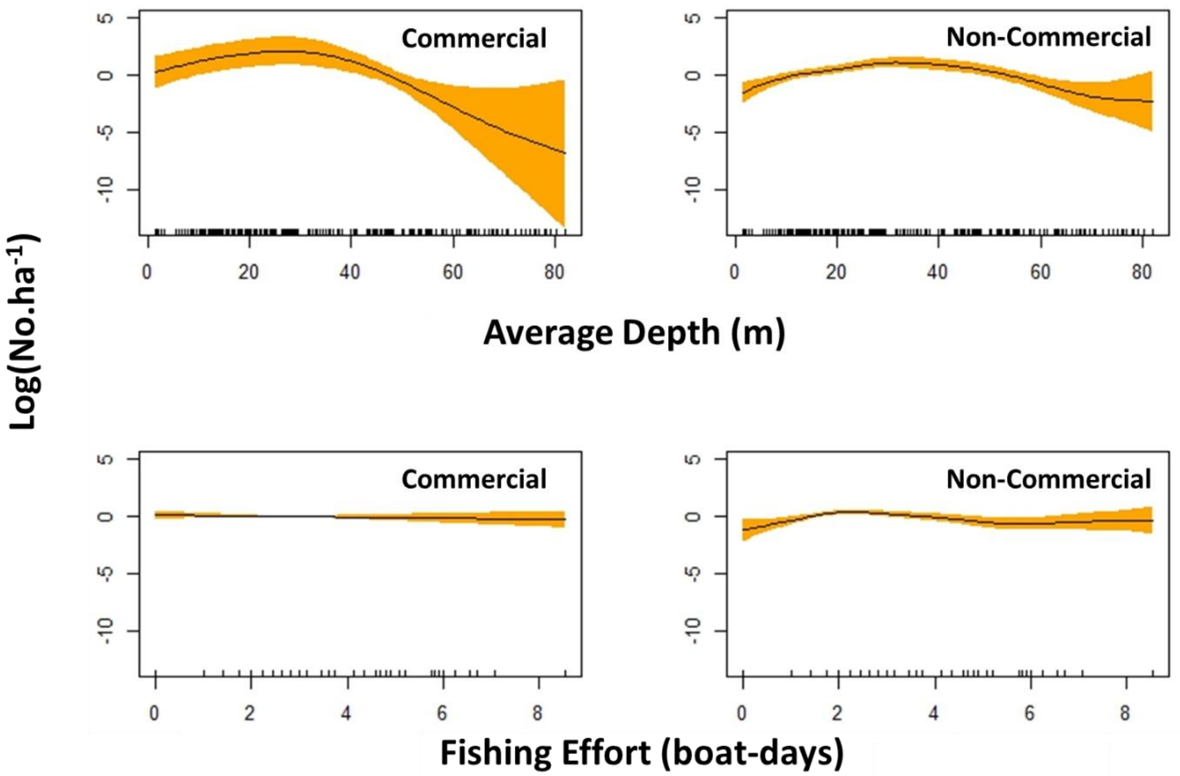


Figure 2.3. GAMM result showing density prediction (no. hectare^{-1}) for commercially targeted species (*A. miliaris*, *H. atra*, *H. fuscogilva*, *H. nobilis*, *Pentard*, *T. ananas*) and non-commercial species (*B. atra*, *B. marmorata*, *B. subrubra*, *H. fuscopunctata*, *H. edulis*, *H. lecanora*, *P. graeffei*, *S. choloronotus*, *S. herrmanni*) across depth and fishing pressure gradient. Fishing pressure was calculated by the taking square root of the number of boat-days for each grid cell of the surveyed area.

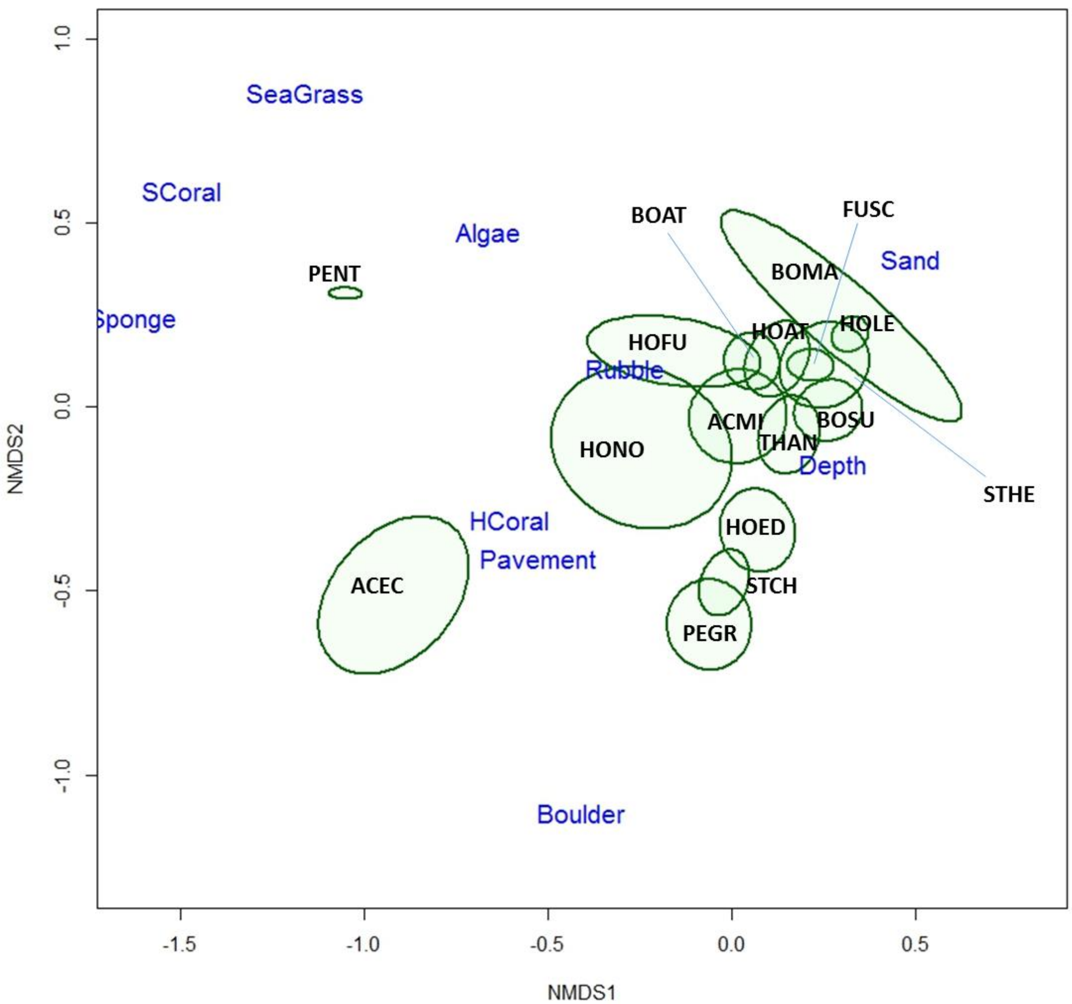


Figure 2.4. Non-metric multidimensional scaling plot showing habitat preference of sea cucumbers at small scale (within 50 cm^2 of the animal) on Mahe plateau, Seychelles. Habitat are written in blue texts at the centroid of site scores. Green ellipses show the 95% confidence interval of each species' habitat preference. Corresponding species code are labeled in black with four letter codes (ACEC: *Actinopyga echinitis*, ACMI: *A. miliaris*, BOAT: *Bohadschia atra*, BOMA: *B. marmorata*, BOSU: *B. subrubra*, FUSC: *Holothuria fuscopunctata*, HOAT: *H. atra*, HOED: *H. edulis*, HOLE: *H. lecanora*, HOFU: *H. fuscogilva*, HONO: *H. nobilis*, PEGR: *Personothuria graeffei*, PENT: Pentard, STCH: *Stichopus chloronotus*, STHE: *S. herrmanni*, THAN: *Thelenota ananas*).

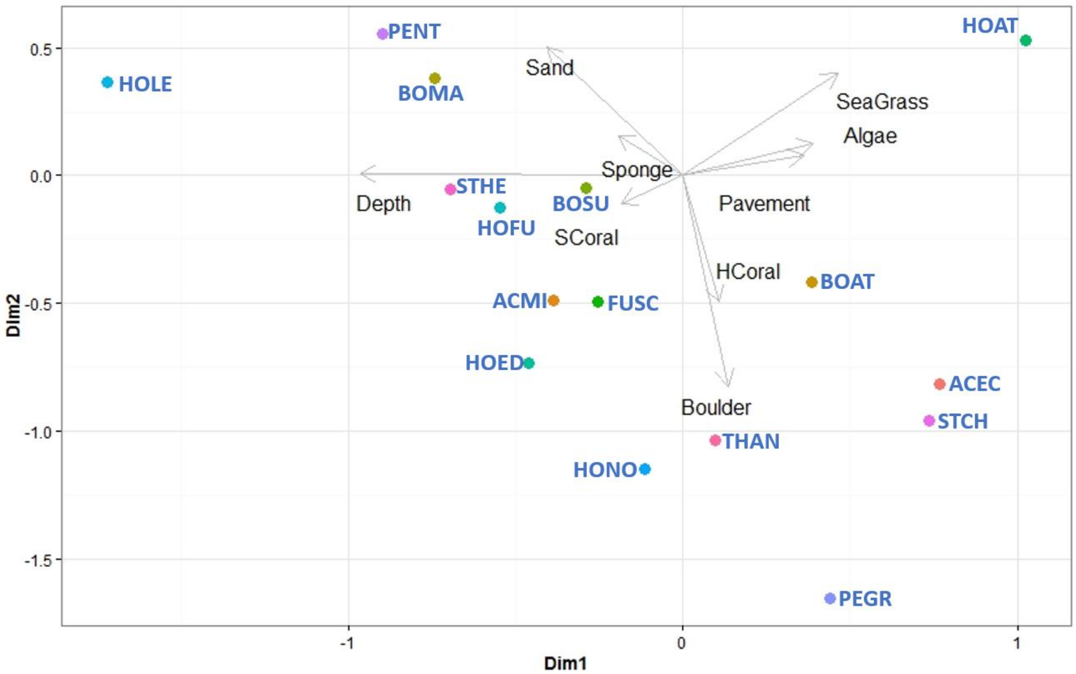


Figure 2.5. Canocnical correspondence analysis (CCA) plot showing habitat preference of sea cucumbers at large scale (about 500m transect) on Mahe plateau, Seychelles. Each species is shown at the centroid of its species score. Species are labeled in four letter codes (ACEC: *Actinopyga echinitis*, ACMI: *A. miliaris*, BOAT: *Bohadschia atra*, BOMA: *B. marmorata*, BOSU: *B. subrubra*, FUSC: *Holothuria fuscopunctata*, HOAT: *H. atra*, HOED: *H. edulis*, HOLE: *H. lecanora*, HOFU: *H. fuscogilva*, HONO: *H. nobilis*, PEGR: *Personothuria graeffei*, PENT: Pentard, STCH: *Stichopus chloronotus*, STHE*: S. herrmanni*, THAN: *Thelenota ananas*).

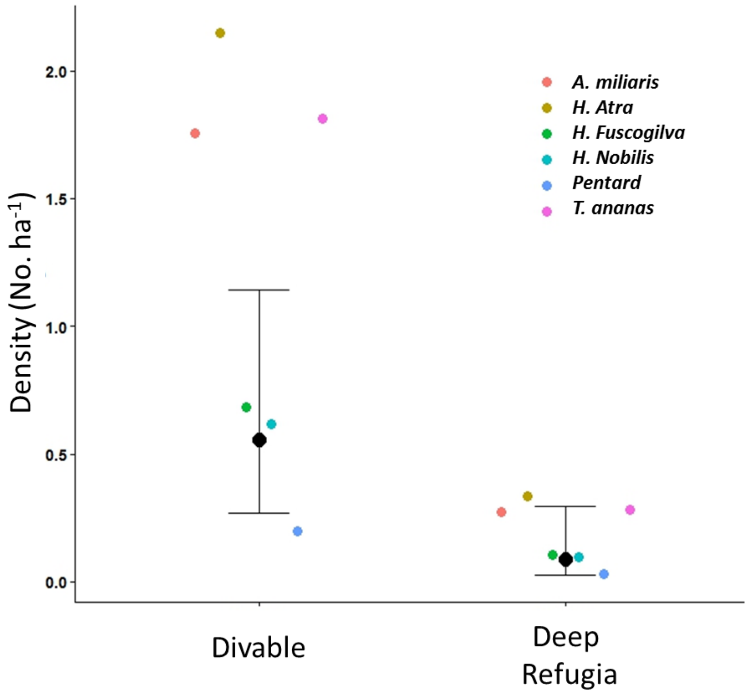


Figure 2.6. Density (no. ha^{-1}) differences between accessible strata (<40m) and non-divable deep-refugia strata (>40m depth) for commercial species. The error bars indicate one standard error.

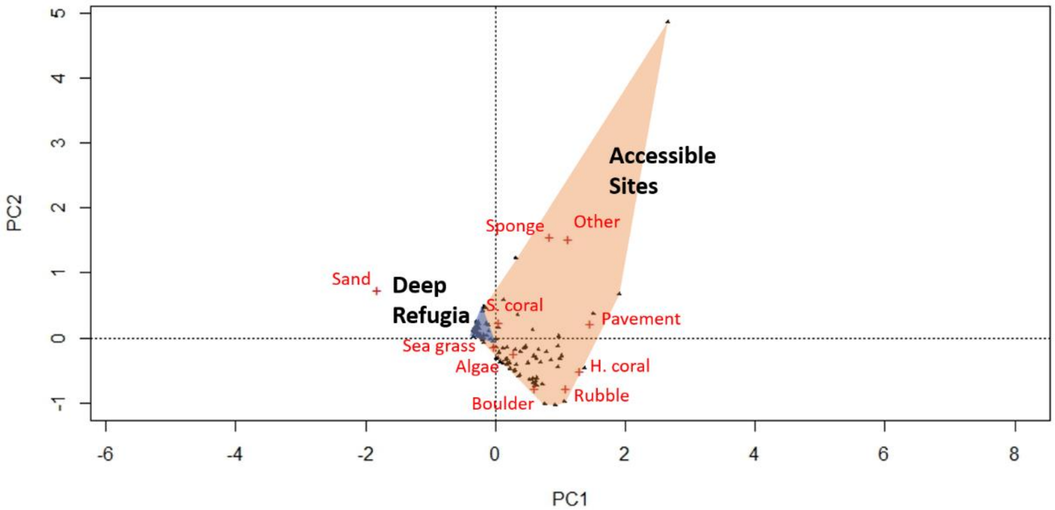


Figure 2.7. Principal component analysis plot showing habitat differences between accessible strata (<40m) and unoperational deep-refugia strata (>40m depth). Deep refugia sites are indicated by blue and shallower accessible sites are indicated by red. Red + are the site scores of each habitat.

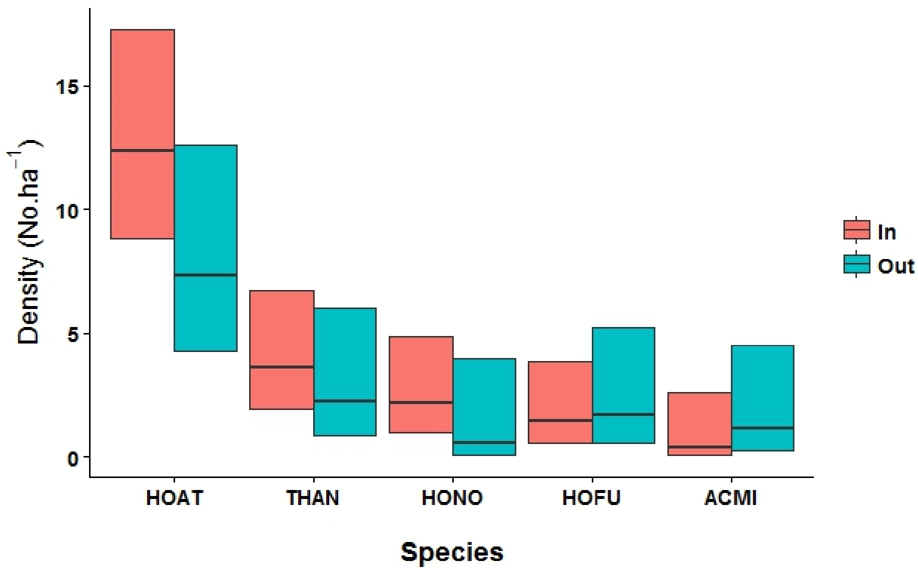


Figure 2.8. Overall species' density found inside and outside of 5 MPAs surveyed. The error boxes are set at 95% confidence interval. Species are labeled in four letter codes (ACMI: *Actinopyga miliaris*, HOAT: *Holothuria atra*, HOFU: *H. fuscogilva*, HONO: *H. nobilis*, PENT: Pentard, THAN: *Thelenota ananas*).

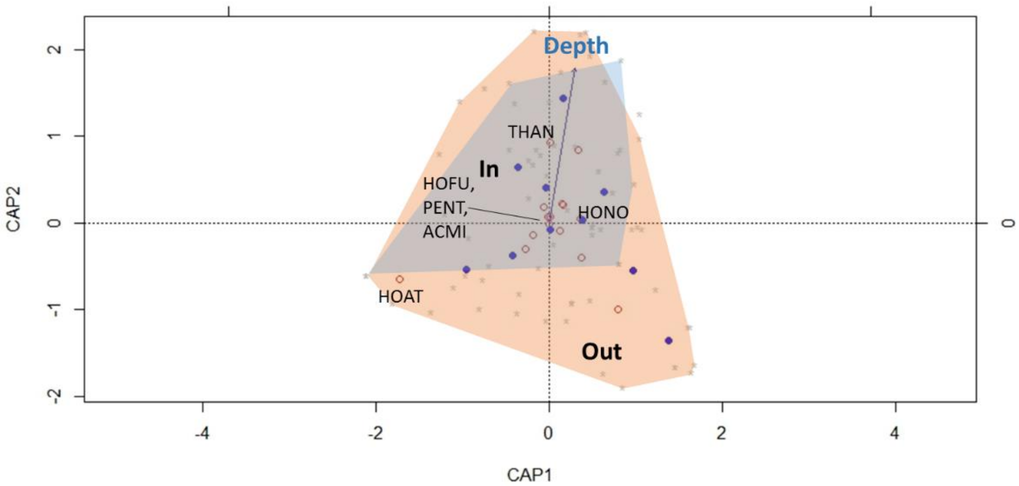


Figure 2.9. Constrained analysis of principal coordinates (CAP) plot showing the difference in species composition inside and outside MPAs. Blue dots indicate the centroids for each MPAs and gray dot indicate each transects. Red dots indicate the centroid for species score with commercially targeted species labeled in four letter codes (ACMI: *Actinopyga miliaris*, HOAT: *Holothuria atra*, HOFU: *H. fuscogilva*, HONO: *H. nobilis*, PENT: Pentard, THAN: *Thelenota ananas*).

CHAPTER III

MASKED DECLINES, VARIABLE CPUE, AND MARKET GROWTH: HOPE OR DESPAIR FOR THE SEYCHELLES' SEA CUCUMBER FISHSERY

To be submitted as:

Koike H., Brodziak J., Gerry, C., Friedlander, A.M. (2017). Masked declines, variable CPUE, and maker growth: hope or despait for the Seychelles' sea cucumber fishery. Fish and Fisheries.

Abstract

Declines in tropical sea cucumber fisheries are common but have scarcely been documented quantitatively. The Seychelles' sea cucumber fishery is a rare case where all fishing vessels have been equipped with VMS and have been required to report their daily catch by species and location since 2000. We used this detailed fishery data to examine the evolution of the fishery, and explored the possibilities of implementing sustainable fishery management strategies. Additionally, because Seychelles' sea cucumbers are harvested strictly for export, we analyzed the market trends from export reports and combined this market information with fishery data to further examine trends in fishermen's income since it was thought to influence regulation acceptance. We found that spatially explicit CPUE showed decline for all species except Pentard, while overall vessels' average CPUE showed few declines, indicating that the stock decline has been masked by the fishing ground expansion. High variance in CPUE regardless of cumulative fishing pressure suggested that 1) fishermen encountered dense "patches" of sea cucumbers randomly, or 2) intrinsic growth rates of sea cucumbers and the associated catch rates differed between high and low quality habitats. The sea cucumber market has been steadily growing and the income analysis of fishery showed that market growth in sea cucumber prices (adjusted for inflation) covered all the loss in revenue caused from the decline in CPUE and the shift in catch composition to lower valued species, thus encouraging fishermen to fish more even as the resource abundance declined. We highlight the importance of accounting for the expansion of fishing grounds, market trends, species differences, and habitat quality when assessing fishery status and trends. Furthermore, we discuss the positive and negative influences of market growth, expanding fishing grounds, and naturally variable catches on the sustainability of future fishery management strategies.

Introduction

For many years sea cucumbers have been a popular delicacy in Japan, China, Korea, and Southeast Asia (Akamine 2001, Kinch et al. 2008, Manez and Ferse 2010). They are easy to catch and have been commercially harvested in the Pacific for centuries (Conand 1990). They are especially sought after as a delicacy in Chinese cuisine known as beche-de-mer. Beche-de-mer is the boiled, dried, and smoked flesh of sea cucumbers which is often used to make soup and stir fry. With the recent increases in economic growth in China and the broader Southeast Asia region, demand for beche-de-mer has increased dramatically (Conand 1998, Purcell 2013).

On pace with the global demand for beche-de-mer, sea cucumber stocks have experienced increased fishing pressure worldwide (Anderson 2011). Since the late 1980s, sea cucumber fisheries have increased to supply growing markets and have expanded beyond historical fishing grounds in Southeast Asia and the western Pacific to new fishing areas off Mexico, Indian Ocean, the Galapagos, and North America (Bruckner et al. 2006). Since the market value of beche-de-mer is extremely high with values of up to 100 USD kg^{-1}, many coastal communities in tropical countries have established sea cucumber fisheries as an important source of income (Anderson et al 2011, Purcell et al. 2009). Most tropical sea cucumber fisheries are small-scale and target multiple species, but despite this, such fisheries often become over-exploited due to a number of common factors including: (1) weak management capacity (Purcell 2013); (2) ease of harvest (Kinch et al. 2008); (3) slow growth of the animal (Conand 1989); and (4) low recruitment (Uthicke 2004, Hearn et al. 2005). In fact, many sea cucumber fisheries around the world have had a boom and bust history (Conand 1990, Anderson et al. 2011). The decimation of sea cucumber stocks has forced moratoria on fishing in places such as

Australia, Mauritius, Mayotte (France), Papua New Guinea, Solomon Islands, Ecuador, and Venezuela (Purcell et al. 2013).

The commercial sea cucumber fishery in the Seychelles has existed since the 1950s (Aumeeruddy and Payet 2005). At that time the fishery was considered unimportant and was an open access fishery with no regulations and no records of harvest (Aumeeruddy and Payet 2005). There was a dramatic increase in landings starting in early 1990s when one of the island-based processors established a direct market with Singapore, which increased the value for Seychelles' beche-de-mer products. However, since there were so few stakeholders, it was not until 1999 that the Seychelles Fishing Authority (SFA) established regulations to restrict access to the fishery through license limitations and mandatory reporting. The number of fishing licenses has been capped at 25 since 2001, and the submission of complete fishery logs is required for annual license renewal.

During the early years of the fishery, fishing grounds were located close to shore and sea cucumbers were harvested in shallow water using snorkeling gear or by handpicking on the reef flats (Aumeeruddy and Payet 2005). However by year 2000, almost all sea cucumbers were harvested using SCUBA gear due to nearshore stock depletion (Aumeeruddy and Payet 2005). Since 2011, all fishing has been boat-based, and each vessel has been allowed to carry up to 4 divers, one cook/helper, and a captain. For safety, all divers are required to have an open water dive certification. Decompression requirements for SCUBA gear with normal compressed air limits the fishing operations to 8-9 paired dives per day, with each dive lasting up to 40 minutes. Usually the vessel has two pairs of divers so that it can rotate its operation while one pair is off gassing (Fig. 3.1a). The divers swim with buoys that have an attached net and the crew on the vessel helps to pull the net up when done. Once the sea cucumbers are retrieved from the net, they are immediately gutted and cured with salt. After several days, most of the water will have evaporated from the sea cucumbers and the salted pieces are stored in the hold for the remainder of the trip (Fig. 3.1b).

The Seychelles took precautionary action to control effort early in the establishment of the fishery, and this allowed this fishery to persist longer than the typical 5 to 8 year time span before most sea cucumber fisheries last before stock depletion (Anderson et al. 2011). Unfortunately, the restrictions on fishing effort were only sufficient to reduce the rate of depletion (Aumeeruddy and Payet 2005). To address concerns of overfishing, the SFA conducted a stock assessment of the sea cucumber fishery in 2004 in collaboration with the Food and Agriculture Organization of the United Nations (FAO). However, the catch limit proposed in that assessment was not accepted by fishermen, and was never implemented. This was partly because the surveys were conducted by the fishery regulators themselves and the results were not trusted by fishermen. More problematically, from a scientific viewpoint, the 2004 stock assessment assumed that the fishery system dynamics were stable and estimated the catch limit using only in-situ observations. However, most sea cucumber fisheries are rarely stable (Anderson et al. 2011), thus it is important that any quantitative stock assessment account for time trends in fishery dynamics and model the system accordingly (Jennings et al. 2009, Smith and Punt 2001).

The detailed nature of the Seychelles sea cucumber fishery data provides a rare opportunity to examine the evolution of this fishery since its inception, and to explore the possibilities of creating sustainable tropical sea cucumber fisheries management strategies. Using these data, we examined the history, catch, and fishing effort of the

Seychelles sea cucumber fishery in order to assess changes in species composition, fishing ground expansion, and trends in market prices over time. Building on these results, we further investigate the factors that drive the continued fishing pressure and suggest possible approaches for sustainable management. We also identify factors to consider when creating stock assessment models. Overall, this analysis can be used to develop effective management options to reverse the slow decline in the Seychelles sea cucumber fishery.

Data collection and methods

Data collection

The history and change in operation methods of the Seychelles sea cucumber fishery were qualitatively and quantitatively analyzed using previously published reports and informal interviews with SFA staff and fishermen. SFA has been recording landings and daily fishing effort for the country's sea cucumber fishery since 2001. Boat captains are responsible for logging their daily operations in a fishery log that records the date, duration of dive, diving depth, number of divers, location (specified by grid cell), and number of each harvested species. The verification of fishery logs is carried out during unloading of sea cucumber at the only port in Victoria, Mahe (Fig. 3.2a, b). SFA provided us with fishery log data from 2000 to 2011. Log data for 2000 and 2001 were omitted due to the high number of unreliable landing reports, such as a small number of registered vessels with daily catch that was an order of magnitude higher than subsequent years. Additionally, SFA has installed vessel monitoring systems (VMS) on all sea cucumber fishing vessels that record the hourly location of each fishing vessel. VMS is used primarily for fisheries enforcement purposes, but can also provide high-resolution spatial and temporal fishing information. SFA has provided us with this VMS data from 2002 to 2011. There have also been several SFA and FAO reports that provide earlier information on the fishery, which is very rare for tropical sea cucumber fishery since most occur in smaller countries with limited research and management capacity.

Market data were collected through SFA internal economic reports and personal communications with fishermen, as well as one of the owner of the three processing facilities. The owner showed interest in sustainable sea cucumber fishery and showed us their processing operation, sample price lists, and their operation history. Operation costs were obtained through informal interviews with sea cucumber fishermen. Additional cost information such as gas and per-diem were estimated using the operation costs from SFA research cruises as a reference.

Data analysis

Seasonality in the fishery

We analyzed the available log data to assess whether there is a distinct seasonal pattern of fishing activity in the Seychelles sea cucumber fishery. The monsoon season occurs between May and October in Seychelles (Abele 1985), which limits long distance travel on open water. Since these rough sea conditions are also a safety concern, SFA has set July to September as a closed season for sea cucumber fishing since 2008. The months of March, April, and November typically have calm seas in the Seychelles and fishers were believed to travel to distant fishing grounds during these months. However, this hypothesis was never tested using fishery log data. To see the typical monthly fluctuation in fishing effort throughout the year, we calculated proportional fishing effort for each month using reported effort data from 2002 to 2011 using the following:

$$P_{E,m,y} = \sum_{v} d_{m,y,v} / \sum_{m} \sum_{v} d_{m,y,v}$$

$$P_{E,m} = P_{E,m,y} / N_y$$

where $d_{m,y,v}$ stands for number of reported days fished by month, year, and vessel, $P_{E,m,y}$ stands for proportional monthly fishing effort by year, N_y is the number of observed years and $P_{E,m}$ is the average monthly fishing effort during 2002-2011. A time series decomposition analysis was conducted to assess the seasonal pattern and trends in fishing effort using the "decompose" function in library "TTR" for R version 3.0.

Based on the observed patterns in nominal fishing effort, we further pooled months into three seasons to test for apparent differences in fishing effort. The "calm season" included March, April, and November, whereas "rough season" included July, August, September; and the remainder was categorized as "normal season". We averaged the monthly effort for each season per boat and used ANOVA and tested for significant differences by season assuming a common normally-distributed variances. In this context, the normality of the common variance was tested using Shapiro-Wilk test and the equality of variance was test using Bartlett's test.

Fishing grounds

We assessed changes in the spatial pattern of fishing effort in the Seychelles sea cucumber fishing grounds using the reported fishing effort and GIS analyses. The Seychelles is geologically unique since the islands are located in the middle of a large granitic plateau with varying depth (Aumeeruddy et al. 2005, Becker et al. 2009). The northern, more populated islands are continental and granitic in origin and are a fragment of the continental masses of India and Madagascar, but were isolated from the beginning of the Tertiary (67 million years ago) as India moved northwards opening up the Indian Ocean (Plummer 1995). This plateau provides a vast amount of accessible habitat that allows sea cucumber fishermen to extend their fishing grounds beyond coastal waters. In order to estimate the area size, we obtained SRTM30_PLUS bathymetry data (Becker et al. 2009) of the area with resolution of 30 arc seconds, and selected an area < 40 m depth using ArcGIS 10.0. A depth of 40 m was thought to be the limit of fishing operation since all dives were conducted using SCUBA with normal compressed air. Limited bottom time at deeper depths greatly reduced the safety of fishermen and cost effectiveness of harvest.

We mapped the spatial fishing pattern through informal interviews and fishery logs in order to identify areas with high fishing effort. In addition to their catch and effort, sea cucumber fishermen in Seychelles are required to identify their fishing location on a 27 km^2 reporting grid. From the logs, the percentage of annual fishing effort for each fishing grid was calculated. This standardized annual effort was averaged for the years from 2002 to 2011 to obtain overall fishing effort allocated to each grid cell. Annual proportion of spatial fishing effort in each grid ($P\_FE_{grid\,,\,year}$) was calculated as: (rewrite the equations with the MS word equation tool using days fished by grid, year, and vessel to compute the proportion of effort in space as done for fishing effort above)

$$P_{E,g,y} = \sum_{v} d_{g,y,v} / \sum_{g} \sum_{v} d_{g,y,v}$$

$$P_{E,g} = P_{E,g,y} / N_y$$

where $d_{g,y,v}$ stands for number of reported days fished by grid, year, and vessel, $P_{E,g,y}$ stands for proportional fishing effort by year for each grid, N_y is the number of observed years and $P_{E,g}$ is the average fishing effort during 2002-2011 for each grid.

Fishing effort

In order to evaluate alternative characteristics of fishing effort in the Seychelles, we investigated the following: 1) fleet size, 2) total number of fishing days, 3) number of fishing days for each fishing grid cell, 4) number of unique grid cells fished for each year, 5) duration of each fishing trips, 6) average distance traveled by each trip, 7) number of grid cells fished for each trip, and 8) size of the area fished. From the fishery logs, we counted unique vessel IDs to obtain the annual fleet size. For fishing effort, we used the number of days as our fishing effort unit, since that was the most accurate and detailed unit available (number of dives and length of dive were not consistently recorded). Unique fishing days for each vessel ID were extracted when calculating fishing days because some boat operators recorded each dive as one record, whereas others recorded one record that included all of the day's fishing. This also avoids double counting the days when fishermen fished in more than one reporting grid, which was occasionally reported separately.

The number of fishing days for each grid cell was calculated for each year. We tested the significance of trend in annual fishing effort that each grid received by fitting least-squares linear regression. Additionally, the number of unique grids fished was counted for each year to test the significance of annual spatial expansion (in number of grids fished) by fitting linear regression.

The number of trip days were counted by grouping daily records as one trip. Groups of records were considered to be one trip if the days were in sequence, with the same vessel ID, and the fished grid cell did not include the harbor. Travel distance for each fishing trip was calculated by creating a line polygon that connected the centroid of each grid cell visited per trip in the order visited. We examined trends in average annual trip distance and average annual number of grid cells visited per trip using least-squares linear regression. The number of years fished for each fishing grid cell was counted and mapped to visually examine the expansion of the fishing grounds over time.

Landing and species composition

We summed yearly landings for each species and divided this by the total landings to examine changes in species catch composition over time. The fishery log recorded catch in numbers caught for each species. We examined the reported catch data for *Holothuria atra*, *H. nobilis*, *H. fuscogilva*, *Thelenota ananas*, *Actinopyga miliaris*, and Pentard (undescribed sp.), since these six species comprised 98% of the total landings. We examined the total landing trend from 2002 to 2011 using robust regression. We further tested change in species composition over time using permutation test on canonical principal coordinate analysis. For this analysis, we calculated species composition by dividing each species' catch by total catch for each year.

Catch per unit effort

We looked at catch per unit effort (CPUE) to analyze 1) annual trends, 2) spatially explicit CPUE, and 3) CPUE difference between vessels. We used each vessel's daily catch (numbers per day) as a measure of CPUE, since fishing effort was measured in number of fishing days. First we calculated overall mean daily CPUE by species for each year to examine the annual trend of CPUE using the following equation.

$$CPUE_{s,y} = \sum_{s}\sum_{y} C_{s,d,y} / \sum_{y} d_y$$

where $CPUE_{s,y}$ stands for annual CPUE for each species, and $C_{s,d,y}$ stands for every reported daily catch for each year and species, and d_y stands for the total number of reported days fished for each year.

Secondly, we looked at spatially explicit CPUE. Because fishing began at different times of the year for each grid cell, use of an overall annual trends was misleading for assessing fishing impacts on the stock. Fortunately, once a grid cell was targeted for fishing, it was typically fished under consistent pressure afterwards. Therefore, we plotted cumulative fishing effort for each grid cell against the respective monthly CPUE at each grid cell for each targeted species ($CPUE_{M,Y,g,s}$) using the following equation:

$$D_{M,Y,g} = \sum_{g}\sum_{y=1}^{Y}\sum_{m=1}^{M} d_{m,y,g}$$

$$CPUE_{M,Y,g,s} = \sum_{s}\sum_{g}\sum_{Y}\sum_{M} C_{d,M,Y,g,s} / D_{M,Y,g}$$

where $D_{M,Y,g}$ stands for cumulative fishing effort at certain year-month (Y, M) for each grid, $d_{m,y,g}$ stands for number of fishing days reported for each year-month at certain grid, and $C_{d,M,Y,g,s}$ stands for every daily catch reported at each grid at given year-month for each species. This calculation allowed us to successfully test the relationship between cumulative fishing effort and catch while removing the spatial expansion effect. Additionally, we categorized fishing grid cells into areas with and without land by merging island shapefiles and fishery grid cells in ArcGIS 10.0. Sea cucumbers are known to have higher density in shallow coastal area (Mercier et al. 2000), thus we tested for differences in CPUE trends between these two strata.

Lastly, we calculated mean daily CPUE for each boat and year to compare differences in CPUE among vessels to see if declines in stock effected all vessels uniformly using the following equation.

$$CPUE_{s,v,y} = \sum_{y}\sum_{v}\sum_{s} C_{s,d,v,y} / \sum_{y}\sum_{v} d_{v,y}$$

where $CPUE_{s,v,y}$ stands for annual CPUE for each vessel and species, and $C_{s,d,v,y}$ stands for every reported daily catch for each year, vessel, and species, and $d_{v,y}$ stands for the total number of reported days fished for each year and vessel. We used ANOVA to see the difference between $CPUE_{s,v,y}$ and used a Bonferroni correction to account for repeated analysis on the same dependent variable and we divided the critical value (α=0.05) by the number of vessels (22).

Market trends

Market force is an important component of the fishery since it often effects fishing pressure. Sea cucumber fishery in the Seychelles is strictly for export, thus export logs were a reliable way to analyze market trends. We obtained export logs from 2006 to 2011 from SFA. These logs contained all the number of beche-de-mer exported, with price for each species. More than 87% of the sea cucumber exports by weight were dried, with the remaining consisting of chilled and salted versions of the product. From these logs, we calculated the yearly average export price for a single beche-de-mer of each species. These prices were further adjusted for inflation using consumer price index (CPI) obtained from The World Bank (2015). We also collected information on price at port through conversation with fishermen. From this information, we concluded that the price of a salted sea cucumber at port is ~ 1/3 of the processed sea cucumber at export. Additionally, we analyzed the destination of the exports, as well as economic importance of this fishery to the Seychelles economy by comparing the total export price with GDP reported by The World Bank (2015).

Gross revenue

Since income is one of the main driver for fishing, we estimated the daily gross revenue for each boat operator for each year from 2007 to 2011. Although export log was available from 2006 to 2011, year 2006 was eliminated from analysis since the market price of *A. miliaris* was not available for that year. We used the daily catch of each vessel and multiplied it by the matching average landing price to analyze the bio-economic effect on fishermen regarding changes in catch composition, CPUE, and market price.

VMS data

We used VMS log to examine each vessel's fishing location and operation in finer detail since VMS records vessel's location (latitude and longitude) and speed at given time interval. Furthermore, Seychelles sea cucumber vessels are all equipped with VMS and are required to have them turned on during fishing operations which protected us from biased sampling. Due to confidentiality issue, we could not link the fishery log to VMS log directly. However, we were able to examine average vessel speed, number of operating vessels at given time, and fishing effort. We further compared the fishing effort estimated from VMS log with fishery log to see the accuracy of their report. Since day light is required for sea cucumber harvest, we truncated the VMS data from 6 am to 6 pm. Furthermore, we truncated these data to only include vessel speed > 0 knots in order to exclude anchored vessels.

Results

Seasonality in the fishery

Overall seasonal fishing effort peaked during the calm weather seasons (March-April, and November-December) and declined during the monsoon season (July – September) (Fig. 3.3a). However, the difference between months declined over the years and showed more uniform distribution of fishing effort throughout the year by 2010 (Fig. 3.3a). The Shapiro-Wilk test of normality indicated that the distribution of monthly fishing effort was non-normal (p= 0007). Based on the ANOVA test for seasonal differences in fishing effort and noting that this test is robust to moderate deviations from normality (Lix et al. 1996), we found that calmer months of March, April, and November had a significantly higher amount of standardized monthly fishing effort ($p<0.01$) than the other normal fishing times, which are May, June and December through February (Fig. 3.3b).

Fishing grounds

Only 27% of the reporting grid cells included areas that were shallow enough for sea cucumber operations. The total area with an estimated bathymetry that was < 40m was 4,349,450 hectares. Fishermen rotated their fishing ground based on ocean conditions and individual area's productivity, which was based on observations by other fishermen and personal past experience. Based on informal conversations with fishermen and SFA personnel, fishing vessel captains followed three general decision rules for choosing fishing locations:

1. If the area (usually around the order of 0.25 ha) was fished by another vessel after the season has started, then they do not go back to that area.
2. If the area was fished within three months of the season, then they may go back to that area at the end of the season.
3. The general waiting time between fishing events in a particular area was between one and three years.

These rules matched with fishery logs, where there were no dominant sites and annual fishing effort was broadly distributed over much of the fishing grounds (Fig. 3.4). Even the heaviest fished grid cell received only 8% of the total adjusted fishing effort and most grid cells received < 4% of the adjusted total effort.

Fishermen constantly searched for new potential fishing grounds by diving in previously unchecked areas. The boat operator often monitors depth on their way to their destination, and if they find an unchecked area shallower than 35m, they send scout divers for possible harvest. If the area is deemed to be a good site (either they find sea cucumbers, or the bottom habitat has some algae, coral, or sea grass), they mark the coordinate of the area to come back in the next season. Assuming this practice has been carried out consistently through the years, it is likely that most diveable sites of the Mahe plateau have been explored since the VMS track record covers the entire plateau (Fig. 3.5).

Fishing effort

All 25 licenses have been issued, but the number of active vessels has fluctuated between 13 and 19 vessels with a gradual decline since 2008. Total fishing effort (in fishing days) increased on average by 100 days each year ($p=0.001$, $sd=22$ days) (Fig. 3.6A), but the average fishing effort expended in each grid cell remained consistent throughout the decade (no significant change over years $p=0.33$) (Fig. 3.6B). However, the number of total grid cells fished increased on average by 6 grids each year ($p<0.01$, $sd=0.52$) indicating that fishermen would not increase their fishing effort in the same place but rather fish different places (Fig. 3.6C). In fact, only 8% of the grid cells were fished every year over the ten recorded years (Fig. 3.7). The average length of a fishing trip increased over time ($p=0.002$), from an average of 3 days (max: 9 days) in 2002 to an average of 7 days (max: 30 days) in 2011 (Fig. 3.6D). The monthly average distance traveled on a fishing trip increased by 267 km (about half the distance of Mahe plateau) during 2002-2011, with fishermen fishing further from port and among more grid cells over time ($p<0.01$) (Fig. 3.6E). The increase in average travel distance was highly variable ($R^2=0.03$) likely due to piracy effect, where shorter traveled distances were observed in 2007-2009 when pirate vessels made it difficult to fish far from port. The increase in distance traveled was also confirmed by the number of gird cells fished per trip, where earlier in the fishery, 3 grid cells, on average, were fished, whereas by 2011, vessels were fishing a significantly higher average of 5 grid cells per trip ($p<0.01$) (Fig. 3.6F).

Landings and species composition

Overall annual total landings of sea cucumbers in the Seychelles have significantly increased from 2002 to 2011 ($p=0.01$). In fact, annual total landing has been increasing since the 1990s except between 2007 and 2009, when vessels had fewer fishing days and could not fish in distant areas due to piracy. The fishery targeted five main species and these were: *H. nobilis*, *H. fuscogilva*, *T. ananas*, *A. miliaris*, and Pentard. Together, these species made up 98% of the total landing. However, the species composition in the fishery has shown a clear shift in targeted species over time (Fig. 3.8 and 9). *H. fuscogilva, H. nobilis,* and *A. miliaris* were the major components of the catch in the first several years of the fishery, joined later by *Thelenota ananas*. Starting around 2005, Pentard rapidly became the dominant harvested species group, comprising up to 60% of the total catch in 2006, while *H. fuscogilva* did not increase in catch thus declined in proportion. Following the decline of *H. fuscogilva*, *A. miliaris* also became less dominant after 2008. *H. nobilis* was already showing signs of depletion in 2002 (when the requirement for fishing logs started) with annual landings of less than 10% of total landings each year. *H. atra* was subsequently targeted in the late 2000s and showed a gradual increase since 2008 (Fig. 3.8 and 3.9). Our permutation test on the canonical principal coordinate showed that 43% of the variance in species composition was explained by years ($p=0.001$) (Fig. 3.9). Thus, both landings and species composition showed significant time trends.

Catch per unit effort

Annual CPUE for reported catches of the five major species showed a slight but significant increase over time ($p<0.01$). The drop in CPUE in 2008 was likely due to Somali piracy, where fishermen avoided long distance trips and were not able to fish in the more remote and productive areas, causing a drop in CPUE. This highlights an important point that CPUE is declining near the main granitic islands of the Seychelles, but this localized decline is masked in the spatially-aggregated CPUE by expansion of fishing grounds. When analyzed at the species level, CPUE showed varying trends where CPUE of *H. nobilis* ($p<0.01$) and *A. miliaris* ($p<0.01$) significantly declined but CPUE of Pentard ($p<0.01$) and *T. ananas* ($p<0.01$) significantly increased (Fig. 3.10). *H. fuscogilva* did not show significant changes in CPUE ($p=0.57$) (Fig. 3.10). Based on our field observations, we speculate that the observed decreases in CPUE could be due to stocks being depleted to the point of rarity (as likely case for *H. nobilis* and *H. fuscogilva*), or could be simply due to a shift in target species (as was likely the case for *A. miliaris*, seeFig. 3.10).

A sharp drop in CPUE for *H. fuscogilva* occurred between 2002 and 2003, but CPUE has remained relatively constant since that time. *H. nobilis* and *T. ananas* both showed relatively low CPUEs in the early years of fishery. However, the daily catch of *H. nobilis* gradually declined from 21 pieces/boat/day in 2002 to 1 piece/boat/day in 2011 (95% decline), whereas the catch of *T. ananas* increased from 6 pieces/boat/day in 2004 to 12 pieces/boat/day in 2011 (200% increase). CPUE for *A. miliaris* was relatively high until 2006 (mean = 126 pieces/boat/day), but declined to nearly 0 in 2010, with a slight increase since that time.

The increase of spatially-aggregated annual CPUE was due to expanding fishing grounds. To remove the masking effect of spatial expansion, CPUE was calculated for each grid cell and plotted against cumulative fishing effort. All species except Pentard showed a significant decline against cumulative fishing pressure (Fig. 3.11). Additionally, we grouped the grid cells with land and without land to test its effect on CPUE since habitat quality for sea cucumbers are usually higher with terrigenous input. For the same four species, grid cells with land had significantly higher (between 1.3 to 2.0 times higher) CPUE than those without land regardless of fishing effort ($p<0.01$). On the other hand, CPUE for Pentard found in grid cells without land produced about 160% more CPUE than those found in grid cells with land ($p<0.01$) (Fig. 3.11).

Overall, the average of the individual CPUE per fishing vessel has gradually increased since 2002, but this increase was not uniform among operators. Fifteen out of the twenty-two vessels showed significant changes in CPUE over time. However, the trend was mixed, with 8 of the 15 vessels showing significant annual increases in CPUE, and the remaining 7 showing significant declines (Fig. 3.12).

Market trends

According to the export log from 2006 to 2013, main export destination for Seychelles' beche-de-mer was Hong Kong, where 89% of the product, by weight, was shipped. Additionally, 4% of the product went to Singapore, with the remaining going to Malaysia, China, Taiwan, and South Africa.

The overall adjusted export price (expressed in 2010 dollars) of beche-de-mer has more than quadrupled from 2006 to 2012. In the year 2006, average price of beche-de-mer exported was 0.83 USD and increased by 845%, with 2012 average export price for the main targeted species at 7.02 USD per piece. This translates to a 2.34 USD profit per individual for fishermen, assuming a 1 to 3 port price to export price ratio estimated from fishermen's comments. We assumed this low price ratio since boats are owned by fishermen, and they directly sell their catch to a processor which also act as an exporter. The highest priced species in 2012 was *H. fuscogilva* (13.71 USD/piece), followed by Pentard (8.45 USD/piece), *H. nobilis* (5.18 USD/piece), and *T. ananas* (6.44 USD/piece). *H. atra* increased dramatically in values from 0.61 USD/piece in 2009 to 6.10 USD/piece in 2010, but no exports were reported for this species after 2010 (Fig. 3.13). This increase in the value of *H. atra* corresponds to an increase in landing records for this species after 2009. Similarly, *A. miliaris* price had a much slower price growth (actually decreased 21% in adjusted price), and resulted in decrease in landing as well.

Gross gains

Although spatially-aggregated CPUE of Seychelles sea cucumbers has not declined overall, the main target species have shifted towards lower value species through time. However, market growth and inflation has more than compensated for declines in CPUE and has even increased the average fishing-day gross income by $147 per year (in adjusted income) for all vessels, even including the ones that showed a significant decline in CPUE ($p<0.01$) (Fig. 3.14).

VMS data

The VMS data showed the different movement patterns of vessels during fishing trips. A density plot of vessel speed for all reporting vessels showed 3 main peaks (Fig. 3.15). The highest peak around 1 knot corresponds to the drift time during harvesting. The second highest peak around 7 knots likely corresponds to the cruising speed used for searching a new fishing area as well as short transits between fishing sites. The lowest peak around 12 knots corresponds to the fast traveling speed when a vessel is not searching for a new fishing area.

If we assume that all vessels that travel between 2.5 knots and 7 knots during daytime hours (6am to 6pm) are fishing, we can calculate the total fishing effort for the fleet from the VMS data alone by summing the number of days that had vessel IDs that were categorized as fishing. Based on this calculation, the VMS data generally showed a higher number of fishing days compared to fishery logs, although the differences were small between the years of 2004 and 2007 (Table 3.1). The observed mismatch between the VMS and fishery log data in 2003 is likely due to the incomplete installation of VMS on all boats in that year. However, the cause of the observed differences after year 2008 is unknown. Additionally, we noticed that the number of unique vessel ID records were different between VMS logs and fishery logs except for 2006. VMS logs showed vessel numbers higher than the permitted 25 licenses but this is likely due to one license holder using multiple boat (Table 3.2).

Discussion

Understanding the history and trends of a fishery system are very important when devising effective resource management strategies. Observing changes in catch per unit effort (CPUE) over time gives us some idea of the health of a stock, under the assumption that CPUE is proportional to abundance over the range of observed stock sizes (Friedlander et al. 2014). This assumption allows one to build simple surplus production models that estimate catch limits (Sparre and Venema 1998). However, using solely CPUE for making management decisions can be risky since CPUE can change for reasons other than changes in stock size (Harley et al. 2001). Changes in the operatational characteristics of the fishery (e.g., changes in gear type, vessel size, and fishing locations) and changes in market characteristics (e.g., changes in prices, costs, and consumer preference) can affect trends in catch and CPUE and hence understanding the impacts of such changes is critical for the development of effective management solutions (Walters and Martell 2004).

Another reason to better understand the characteristics of the fishery is for modeling purposes. Some conventional stock assessment models assume stable fishery system and do not account for changes in catchability due to gear improvement, shifts in target species, expansion of fishing grounds, or changes in fishing costs and market price (Quinn and Deriso 1999, Walters and Martell 2004). However, these fishery characteristics often change over time in an important manner and are therefore critical to investigate and model for an accurate stock assessment.

The style and scale of the Seychelles sea cucumber fishery has changed over time. It has followed the typical pattern of rapid development of the fishery, followed by signs of stock depletion, such as expansion in fishing ground and changes in landed species composition. However, this decline happened much more gradually compared to the rest of the known tropical fishery likely because: 1) the Seychelles sea cucumber fishery capped its fleet size at 25 since 2002, and 2) large productive plateau dissipated the fishing pressure.

This study examined the seasonal trends, landed species composition, fishing grounds, CPUE trends, and market trends of Seychelles' sea cucumber fishery in detail. Combining these detailed information, we provided insight into: 1) fishing pattern; 2) CPUE trend free from the compensating effect of spatial expansion; and 3) fishermen perception of the fishery and market growth.

Fishing pattern

Seychelles sea cucumber fishery is not limited to its small coast line, but supported by the large and productive plateau surrounding the main granitic islands. The fishing ground size is comparable to some of the well managed coastal sea cucumber fisheries in Australia (Eriksson and Byrne 2013). Sea cucumber fishermen in the Seychelles fish the entire plateau by basing their operation from boat and taking long fishing trips. They are now fishing more days, travelling longer distances, and are harvesting more species compared to 10 years ago. Season with calm ocean conditions had higher fishing effort in the early years, but this seasonal difference has diminished over time as fishermen now fish more during the harsher condition months, likely as a result of high income return and lower catch rate in proximal ocean.

Fishermen are traveling longer distance, which also contributes to more fishing days. To make these longer trip worthwhile, fishermen also stay at sea for a longer period of time ($p=0.002$), and fish more areas in one trip than in earlier stage of the fishery ($p<0.01$). We initially expected to detect areas with high fishing pressure associated with "good habitats" for sea cucumbers. However, no such areas were identified since fishing effort were thinly distributed across the entire plateau. There was, however, a slight tendency toward area adjacent to land due to better catches and shallower depths, which allowed for longer dive times.

CPUE trend without the spatial expansion effect

CPUE is often used as an indicator of fishery health (Sparre and Venema 1998). Overall, the fishery is healthy when CPUE stays constant or increases slightly over time (Friedlander et al. 2014). In the case of the Seychelles sea cucumber fishery, there was an increase in annual CPUE due to the fishery expanding to new, unexploited areas, masking the declines in CPUE in areas that had been fished previously. A case in point occurred between 2007 and 2009 when CPUE declined because fishing was restricted to nearby areas due to security concerns related to Somali piracy. When we removed the masking effect of the spatial expansion of the fishery by plotting catch against cumulative fishing effort, catch rates for all species except Pentard declined with increased fishing effort. Declines in CPUE for *H. fuscogilva*, *H. nobilis*, and *T. ananas* are likely related to stock depletion. However, we believe declines in *A. miliaris* are due to decreased targeting by fishermen rather than stock decline since we detected no density difference of *A. miliaris* from 2004 to 2011 from field surveys. *A. miliaris* was the only species that did not show strong growth in market price, thus fishermen could have seen this specie as less profitable and harvested less. *H. fuscogilva* and Pentard had higher overall CPUEs compared to the other three species. This could suggest that these two species have stronger aggregation behavior compared to the other species, allowing fishermen for more efficient harvesting.

When we just looked at the fishing effort, fishing grid cells containing land was more fished compared to those without land ($p<0.01$). Nevertheless, grid cells with land had significantly higher CPUE than those without land for all species with the exception of Pentard ($p<0.01$). The presence of land likely provides: 1) better quality habitat with high productivity and terrigenous inputs and 2) shallower areas allowing longer dive/harvest time, thus leading to higher CPUE.

We did not see any concentration of large catches at low cumulative fishing pressure in Fig. 3.9. This indicates that high density “pockets” of sea cucumbers were not selectively fished, but instead were fished based on random encounters. Confirming this, Seychelles’ sea cucumber fishermen had occasional high catch even at heavily fished area likely caused by this random encounter of “pockets”. However, area with less cumulative fishing effort does provide higher encounter rate for dense pockets of sea cucumbers. This incentivizes fishermen to search for new fishing grounds as seen in the spatial expansion of the fishery.

Fishermens' perception of the fishery and market growth

Fishermen have compensated for stock declines by developing new fishing grounds, but the annual increase in CPUE was not equally felt by fishermen. Only 36% of the boat operators have actually increased their daily catch from 2002 to 2011, while 33% of the fleet showed decline in catch, and remaining fleet did not significantly change in landings. Additionally, fishermen have also started to harvest lower value species to increase their income. In a typical fishery, declining catch and increasing lower value species lead to declining income for fishermen. However, this was not the case for sea cucumber fishery. Market prices have increased so rapidly that not only did it cancel any losses from declining catch and species shift, but has even increased fishermen's gross daily income by 2-3 times over the decade. Therefore, fishermen do not feel a decline in the fishery and have few economic incentives to decrease their effort.

Stock assessment implications

Our assessment revealed the following points that need to be considered when assessing sea cucumber stocks: 1) standardize the fishing ground expansion; 2) standardize unequal fishing efficiency caused by species difference (e.g. *T. ananas* are naturally found in low density compared to *H. atra*); 3) standardize unequal fishing efficiency caused by different habitats (e.g. density difference caused by presence/absence of land); and 4) determine if changes in CPUE are driven by reasons other than stock declines (e.g. a decline in CPUE for *A. miliaris* was likely caused by low market value).

Fishing ground expansion is a common trend seen in many sea cucumber fishery (Toral-Granda et al. 2008, Purcell 2013), and one that causes a delay in the detection of stock depletion (Walters and Martell 2004). It is essential that fishery logs include spatial references at logical scales to allow for accurate detection in CPUE changes and standardization. Fishing efficiency also needs to be standardized for stock assessment since differences in CPUE occur among species and fishing area. For example, *H. fuscogilva* and Pentard were caught in higher numbers compared to the other three species consistently. This means stocks needs to either be assessed at an individual species level, or fishing efficiency needs to be standardized based on what fishermen are targeting for that fishing event. We also found that grid cells with land had higher catch than those without land for most species. Therefore, we suggest that the fishing efficiency also be standardized by the area fished when assessing the stock. Changes in CPUE due to non-fishing factors, such as market interests, are difficult to detect unless one has access to fishery-independent data. Since only a few countries influence the market, we recommend conducting fishery-independent surveys when possible. It will also be important to closely follow market trends.

Hope for the future

We believe that Seychelles has a potential to become one of the few sustainable tropical sea cucumber fisheries owing to its large plateaus, noisy catch, market growth, small number of stake holders, and VMS. Seychelles' unique productive plateaus indeed hide the declining CPUE, but also dissipate fishing pressure. Furthermore, it could provide rotational harvest management option. Rotational harvest system for sea cucumbers are challenging in areas with smaller fishing grounds, since sea cucumbers are slow growing and require ample rest periods (Purcell 2010, Purcell et al. 2013). Seychelles' large plateau could provide this long rest time, since fishermen would take a while to finish their rotational cycle.

The recruitment failure caused by the low density (Allee et al. 1949, Courchamp et al. 1999) are thought to be one of the reason for stock collapse and slow recovery (Shepherd et al. 2004, Uthicke et al. 2004). Seychelles' noisy landing data indicate that fishermen are still encountering high densities of sea cucumbers even in heavily fished area. This could mean that Seychelles still have stock density above the threshold of Allee effect for effective restocking.

Stakeholder acceptance of management regulations is the key for a successful sustainable fishery (Hoggarth 2006, Österblom et al. 2011). We believe that sea cucumber fishery in Seychelles has an advantage in stake holder acceptance compared to many other fisheries since 1) strong market growth could allow fishermen and stakeholders to maintain current levels of income while reducing harvest levels; 2) the number of stakeholders involved is small compared to other sea cucumber fisheries; and 3) fishery is strictly for export and is not directly tied to food security (Garcia and Rosenberg 2010). Currently, market growth has already interested processors in sustainable fishery since they have a long-term capital investment, and see that market prices are projected to increase in the future. On the other hand, most fishermen are not convinced to accept new management regulations since they have growing income. However, both group like to see this fishery last for a while. This is the benefit of having few stake holder groups because there are less contradicting management goals such as finding balance between ecotourism and securing food source. Getting a consensus among stakeholders to accept management regulation would have been much harder if this fishery was supplying essential protein source so that reduction in catch led directly to starvation.

Lastly, Seychelles' sea cucumber fishery is one of the only small scale fishery that has VMS installed in all fishing vessels. This allows for much efficient regulation enforcement and finer spatial resolution to be used for management planning.

Management recommendations

To achieve sustainable harvest, it is important to develop input (e.g., vessel size, species limit, etc.), and output controls (e.g., size limit, catch limit) that match with enforcement capacity (Purcell and Pomeroy 2015). Currently SFA only controls input effort through vessel numbers and specified fishing months (Table 3.3). In addition to these input controls, SFA could also limit area (e.g. rotational harvest) or species that can be fished to further decrease fishing pressure. Limiting fishing areas and months are relatively easy to enforce in the Seychelles since all fishing vessels are equipped with VMS. Furthermore, SFA should set catch limits for output control. This is easy to implement for Seychelles since SFA already records and check the catch at the site of landing and export. We would not recommend size limit since that would be very time consuming and unrealistic to enforce.

If managed well, sea cucumber fishery has the potential to become an important fishery for small tropical countries. For Seychelles' case, in 2011, the Seychelles GDP was 1.065 billion USD (World Bank 2015) and the total value for Beche-de-Mer exported in Seychelles for that same year was reported to be 4 million USD. This indicates that the sea cucumber fishery with only 25 vessels was responsible for 0.3% of the nation's GDP. Therefore, sustainability of the fishery is important for both Seychelles' government and fishery stake holders. With fishing pressure reaching close to its limit for spatial expansion, it is more crucial than ever for fisheries managers, scientists, and stakeholders to work closely to develop sustainable practices.

References

Akamine, J. (2001) Holothurian exploitation in the Philippines: continuities and discontinuities. *Tropics* 10, 591–607.

Allee, W.C., Park, O., Emerson, A.E., Park, T. and Schmidt, K.P. (1949). *Principles of animal ecology*. Edn 1. WB Saundere Co. Ltd.

Anderson, S.C., Flemming, J.M., Watson, R. and Lotze, H.K. (2011). Serial exploitation of global sea cucumber fisheries. *Fish and Fisheries*, 12(3), 317-339.

Aumeeruddy, R. and Payet, R. (2005). Management of the Seychelles sea cucumber fishery: status and prospects. *FAO Fisheries Technical Paper*, 239-246.

Aumeeruddy R, Skewes T, Dorizo J, Carocci F, Coeur de Lion F, Harris A, Henriette C, Cedras M. (2005). *Resource assessment and management of the Seychelles sea cucumber fishery*. FAO Project Number: TCP/Seychelles/2902(A), November 2005. 49 pp.

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., ... & Weatherall, P. (2009). Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. *Marine Geodesy*, 32 (4), 355-371.

Bruckner, A.W. (2006). *Sea cucumber population status, fisheries and trade in the United States. In: Proceedings of the CITES Workshop on the Conservation of Sea Cucumbers in the Families Holothuriidae and Stichopodidae (ed. A.W. Bruckner)*. NOAA Technical Memorandum NMFS-OPR- 34, Silver Spring, MD, USA, pp. 192–202.

Conand, C. (1989). *Les holothuries aspidochirotes du lagon de Nouvelle-Cale´donie: biologie, e´cologie et exploitation*. PhD Thesis, Universite´ de Bretagne Occidentale, Brest.

Conand, C. (1990). *The Fishery Resources of Pacific Island Countries. Pt. 2: Holothurians*. FAO Fisheries Technical Paper 272.2, FAO, Rome.

Conand, C. (1998). *Overexploitation in the present world sea cucumber fisheries and perspectives in mariculture.* In: Echinoderms: San Francisco: Proceedings of the Ninth International Echinoderm Conference, San Francisco, California, USA, 5–9 August (eds R. Mooi and M. Telford). A.A. Balkema, Rotterdam, pp. 449–454.

Courchamp, F., Clutton-Brock, T. and Grenfell, B. (1999). Inverse density dependence and the Allee effect. *Trends in Ecology & Evolution*, 14(10), 405-410.

Eriksson, H. and Byrne, M. (2013). The sea cucumber fishery in Australia's Great Barrier Reef Marine Park follows global patterns of serial exploitation. *Fish and Fisheries*, 16(2), 329-341.

Friedlander, A. M., Nowlis, J. and Koike, H. (2014). Improving fisheries assessments using historical data. *Marine Historical Ecology in Conservation: Applying the Past to Manage for the Future*, 91.

Garcia, S.M. and Rosenberg, A.A. (2010). Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365 (1554), 2869-2880.

Harley, S.J., Myers, R.A. and Dunn, A. (2001). Is catch-per-unit-effort proportional to abundance? *Canadian Journal of Fisheries and Aquatic Sciences*, 58(9), 1760-1772.

Hearn, A., Martinez, P. and Veronica, T.G. (2005) Population dynamics of the exploited sea cucumber Isostichopus fuscus in the western Galapagos Islands, Ecuador. *Fisheries Oceanography*, 14, 377–385.

Hoggarth, D.D. (2006). Stock assessment for fishery management: *A framework guide to* *the stock assessment tools of the fisheries management and science programme* (No. 487). Food & Agriculture Org.

Jennings, S., Kaiser, M. and Reynolds, J.D. (2009). *Marine Fisheries Ecology*. John Wiley & Sons.

Kinch, J., Purcell, S., Uthicke, S. and Friedman, K. (2008). Population status, fisheries and trade of sea cucumbers in the Western Central Pacific. In: Sea Cucumbers: A Global Review of Fisheries and Trade (eds V. Toral- Granda, A. Lovatelli and M. Vasconcellos), *FAO Fisheries and Aquaculture Technical Paper,* 516, 7–55.

Lix, L.M., J.C. Keselman, and H.J. Keselman. (1996). Consequences of assumption violations revisited: A quantitative review of alternatives to the one-way analysis of variance F test. *Rev. Educ. Res.*, 66, 579-619.

Mercier A., Battaglene, S. C., Hamel, J. F. (2000). Settlement preferences and early migration of the tropical sea cucumber Holothuria scabra. *Journal of Experimental Marine Biology and Ecology*, 249 (1), 89-110.

Manez, K.S. and Ferse, S.C.A. (2010) The history of Makassan trepang fishing and trade. *PLoS ONE*, 5, e11346.

Österblom, H., Sissenwine, M., Symes, D., Kadin, M., Daw, T. and Folke, C. (2011). Incentives, social–ecological feedbacks and European fisheries. *Marine Policy*, 35(5), 568-574.

Plummer PS (1995) Ages and geological significance of the igneous rocks from Seychelles. *Journal of African Earth Sciences,* 20, 91-101.

Purcell, S.W., Gossuin, H. and Agudo, N.S. (2009) Status and Management of the Sea Cucumber Fishery of La Grande Terre, New Caledonia. *WorldFish Center Studies and Review,* 1901.

Purcell, S.W. (2010). *Managing sea cucumber fisheries with an ecosystem approach.* Edited by Alessandro Lovatelli, Marcelo Vasconcellos, and Yimin Ye. Food and Agriculture Organization of the United Nations.

Purcell, S.W. and Pomeroy, R.S. (2015). Driving small-scale fisheries in developing countries. *Frontiers in Marine Science*, 2, 25.

Purcell, Steven W., Mercier, A., Conand, C., Hamel, J. F., Toral- Granda, M. V., Lovatelli, A., and Uthicke, S. (2013). Sea cucumber fisheries: global analysis of stocks, management measures and drivers of overfishing. *Fish and Fisheries*, 14.1, 34-59.

Quinn, T.J. and Deriso, R.B. (1999). *Quantitative fish dynamics*. Oxford University Press.

Smith, T. and Punt, A.E. (2001). The gospel of maximum sustainable yield in fisheries management: birth, crucifixion and reincarnation. *Conservation of Exploited Species*. Edited by JD Reynolds, GM Mace, KH Redford, and JG Robinson. Cambridge University Press, Cambridge, UK, 41-66.

Shepherd, S.A., Martinez, P., Toral-Granda, M.V. and Edgar, G.J. (2004). The Galápagos sea cucumber fishery: management improves as stocks decline. *Environmental Conservation*, 31(02), 102-110.

Sparre, P. and Venema, S.C. (1998). *Introduction to Tropical Fish Stock Assessment-Part 1: Manual*, Rome, FAO.

Abele, L. G. (1985). Biogeography and ecology of the Seychelles Islands. *Science*, 227, 160-162.

Toral-Granda, V., Lovatelli, A. and Vasconcellos, M. (2008). *Sea cucumbers. A global review of fisheries and trade*. FAO Fisheries and Aquaculture Technical Paper, 516.

Uthicke, S. (2004). *Over fishing of sea cucumbers: lessons from the Great Barrier Reef. In: Advances in Sea Cucumber Aquaculture and Management* (eds A. Lovatelli, C. Conand, S. Purcell, S. Uthicke, J.-F. Hamel and A. Mercier), FAO Fisheries Technical Paper No. 463, FAO, Rome, pp. 163–171.

Walters, C.J. and Martell, S.J. (2004). *Fisheries ecology and management*. Princeton University Press.

World Bank. (2015). *World Development Indicators 2015*. Washington, DC.

Table 3.1. Fishing days calculated from VMS log and fishery log. Percent difference is calculated by ((Fishing_days$_{Log}$-Fishing_days$_{VMS}$)/Fishing_days$_{VMS}$)

Year	Number of fishing days from VMS	Number of fishing days from fishery logs	% difference
2002	NA	269	NA
2003	8	678	8375%
2004	1039	1065	3%
2005	1160	1068	-8%
2006	1503	1190	-21%
2007	1436	1324	-8%
2008	385	1170	204%
2009	2462	1290	-48%
2010	205	1245	507%
2011	167	1537	820%

Table 3.2. Number of unique vessel ID recorded for each year by VMS and Fishery Logs.

Year	Number of unique vessel IDs from VMS	Number of unique vessel IDs from Fishery Log
2002	NA	13
2003	1	13
2004	13	19
2005	15	17
2006	18	18
2007	22	18
2008	21	17
2009	32	15
2010	3	14
2011	3	13

Table 3.3. Management capacity of Seychelles' sea cucumber fishery

	Control Type	Action
Input Control	Fleet size limit	25 license cap
	Season limit	Closed seasons between July and September
	Species limit	--
	Fishing Ground limit	--
Output Control	Size limit	--
	Catch limit	--
Enforcement Capacity	VMS monitoring system	All vessels are equipped and turned on during operation
	Landing site inspection	Check with fishery log
	Export site inspection	Check with processor report
	Poaching prevention	Rely on personal reporting

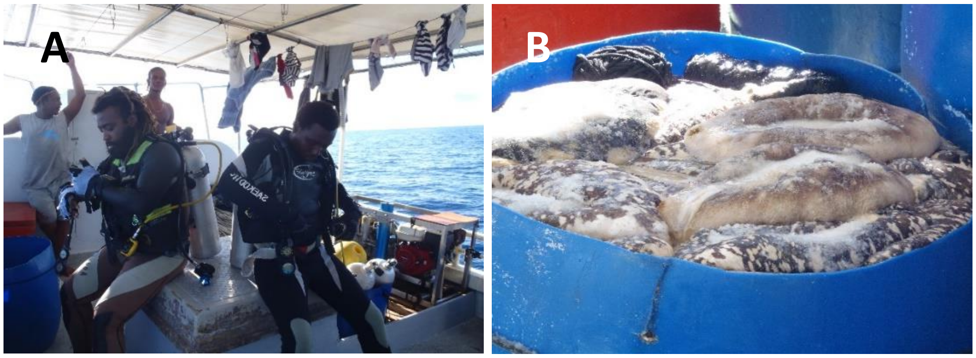


Figure 3.1. Seychelles sea cucumber fishery operation scenes. (A) Fishers preparing for their collection and (B) Sea cucumbers are immediately gutted, salted, and then stored.

Figure 3.2. Seychelles sea cucumber fishery operation scenes. (A) Unloading of sea cucumbers at the port in Victoria, Mahe, (B) Fishermen unloading salted sea cucumbers while SFA workers check the fishery log.

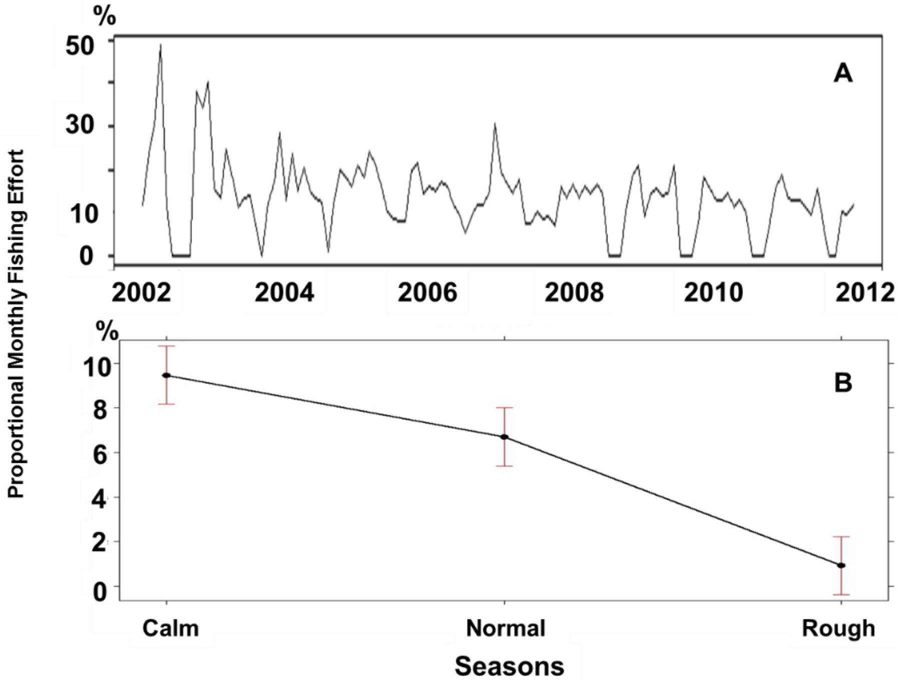


Figure 3.3. (A) Fishing effort (in monthly proportions) allocated to each month for each year. (B) Standardized fishing effort differences between seasons.

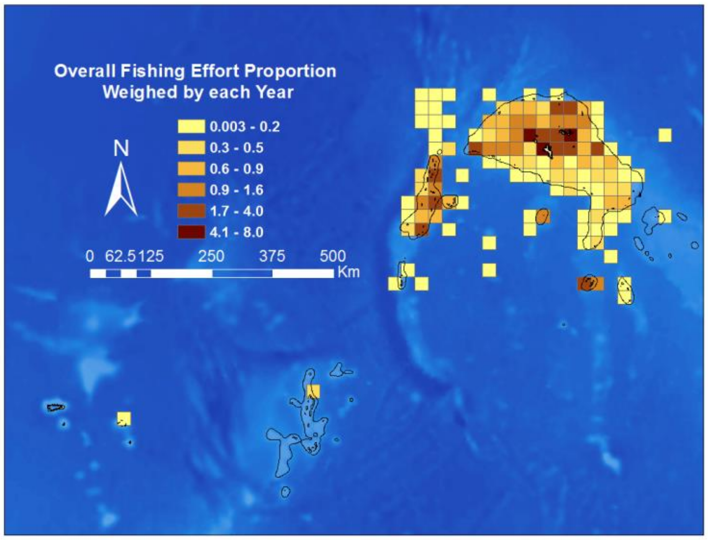


Figure 3.4. Annual sea cucumber fishing effort allocated over each fishing grid cell. Lighter yellow indicates lighter fishing effort. Fishing effort is corrected by standardizing annual fishing effort for each cell into percentage and taking the average over the years. Black line delineates the plateau.

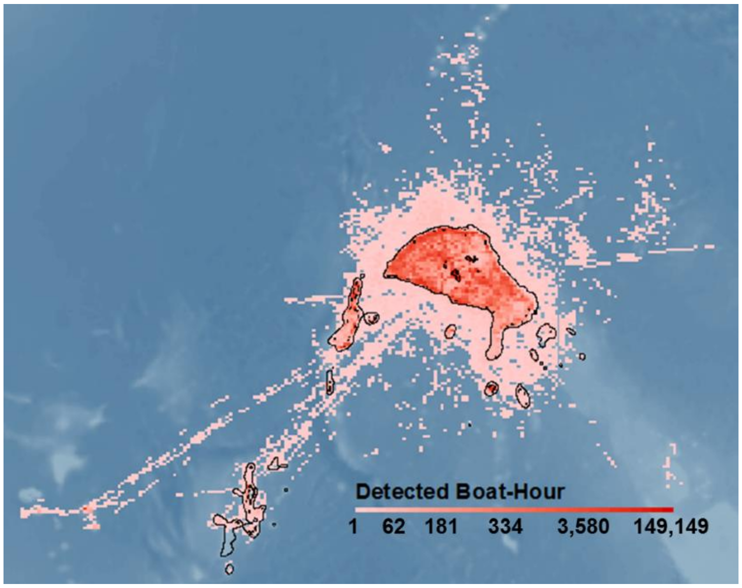


Figure 3.5. Cumulative VMS tracks below 5 knots from 2002 to 2009. Black line delineates the plateau.

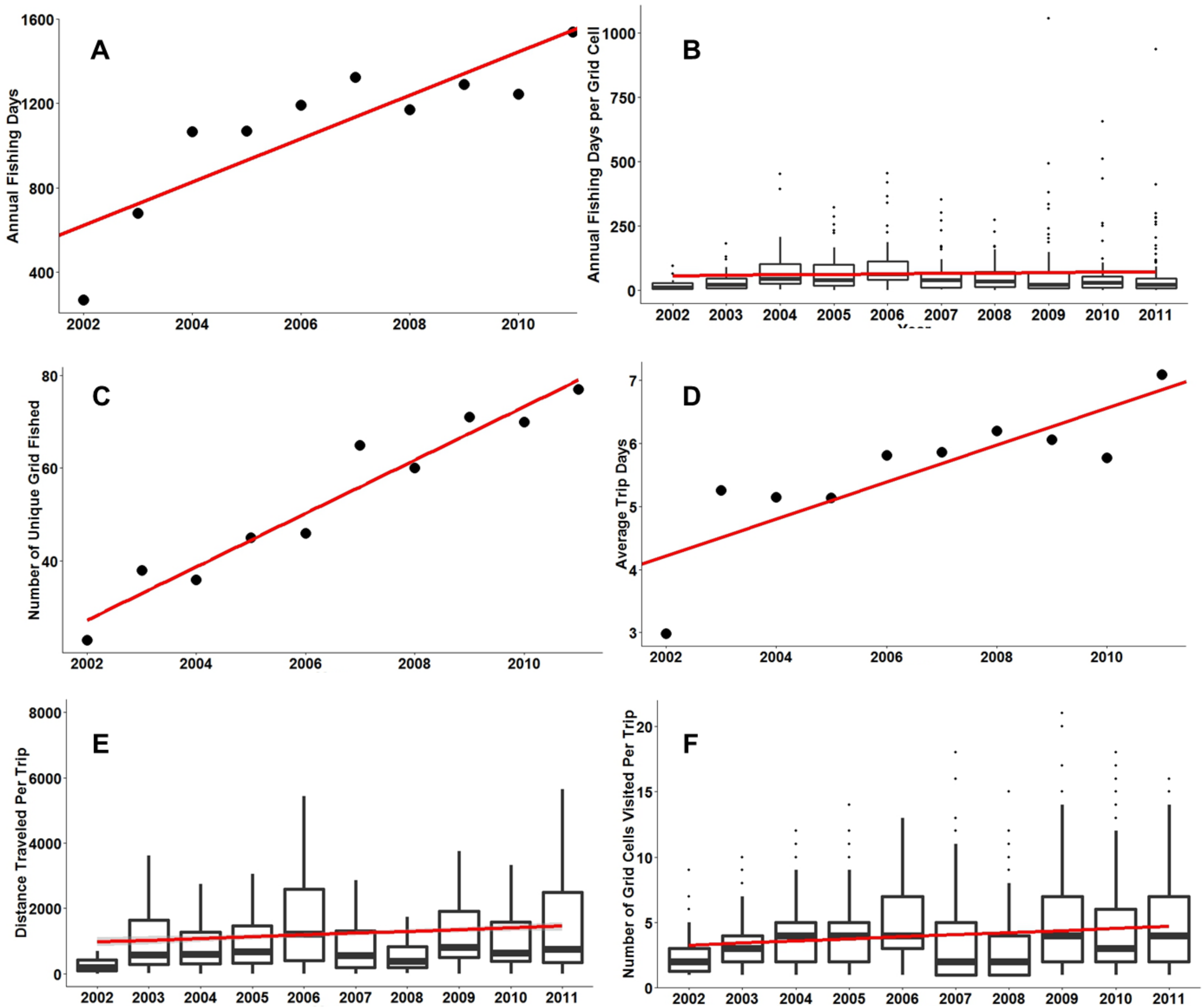


Figure 3.6. (A) Annual fishing effort shown in total fishing days for each year with red line depicting the yearly trend (p=0.001, R^2=0.71), (B) Total days fished in each grid cell per year with red line depicting the yearly trend (p=0.33, R^2=0.001), (C) Total number of unique grid cells fished per year with red line depicting the yearly trend (p<0.01, R^2=0.93), (D) Average trip days per year with red line depicting the yearly trend (p=0.002, R^2=0.65), (E) Average trip distance per year with red line depicting the yearly trend (p<0.01, , R^2=0.01), and (F) Number of grid cells visited per trip for each year with red line depicting the yearly trend (p<0.01, R^2=0.02).

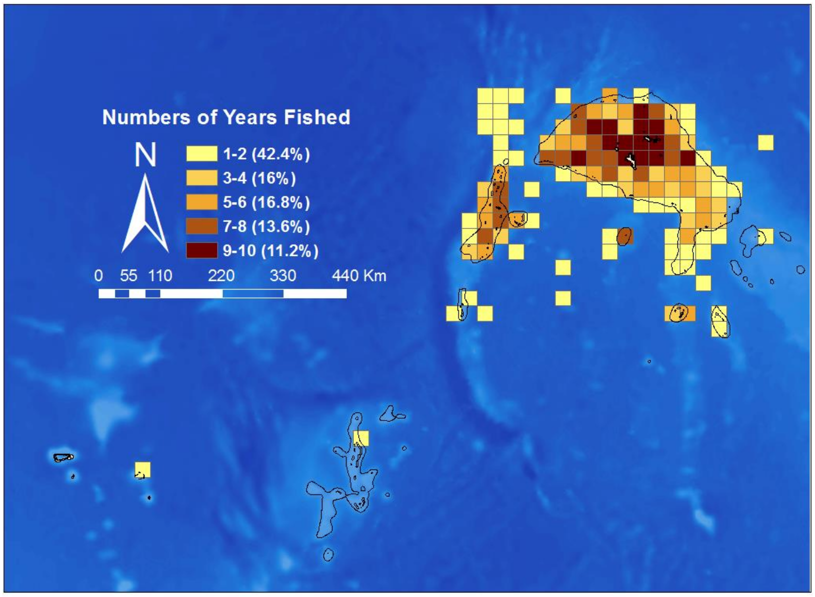


Figure 3.7. Expansion of fishing ground from main fishing grounds depicted with lighter colored grids indicating fewer years fished. Numbers in parentheses indicate the percentage of grid cells for each year category. Black line delineates the plateau.

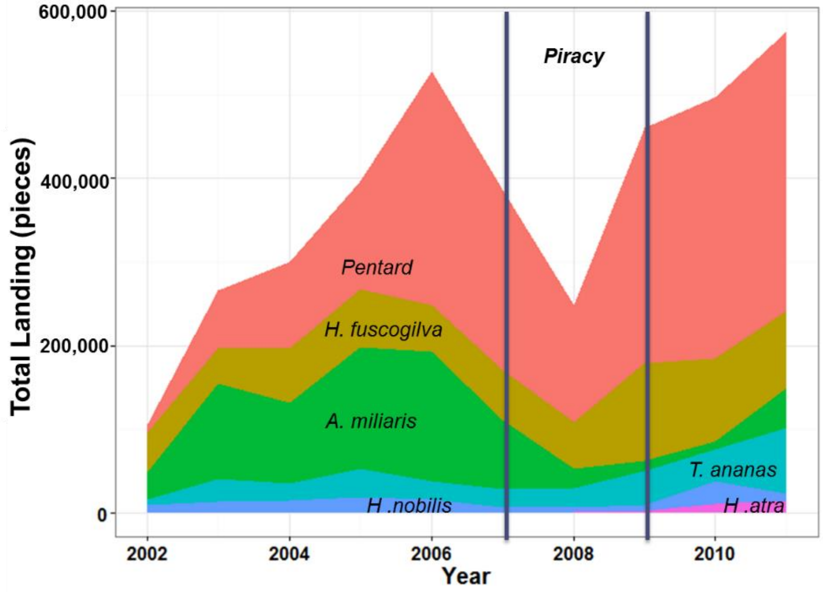


Figure 3.8. Species composition of sea cucumber landing in the Seychelles between 2002 and 2011. Piracy created a drop in landing pieces between 2007 and 2009.

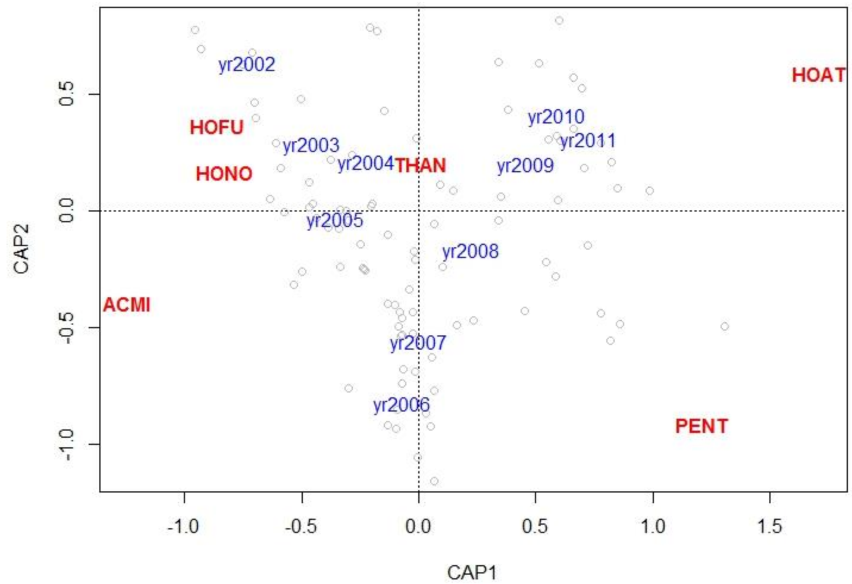


Figure 3.9. Canonical principal coordinate analysis showing change in targeted species composition over years. Red letter indicates centroid for each species (ACMI: Actinopyga miliaris, HOAT: *Holothuria atra*, HOFU: *H. fuscogilva*, HONO: *H. nobilis*, THAN: *Thelenota ananas*, PENT: Pentard). Blue letter shows the centroid of each year.

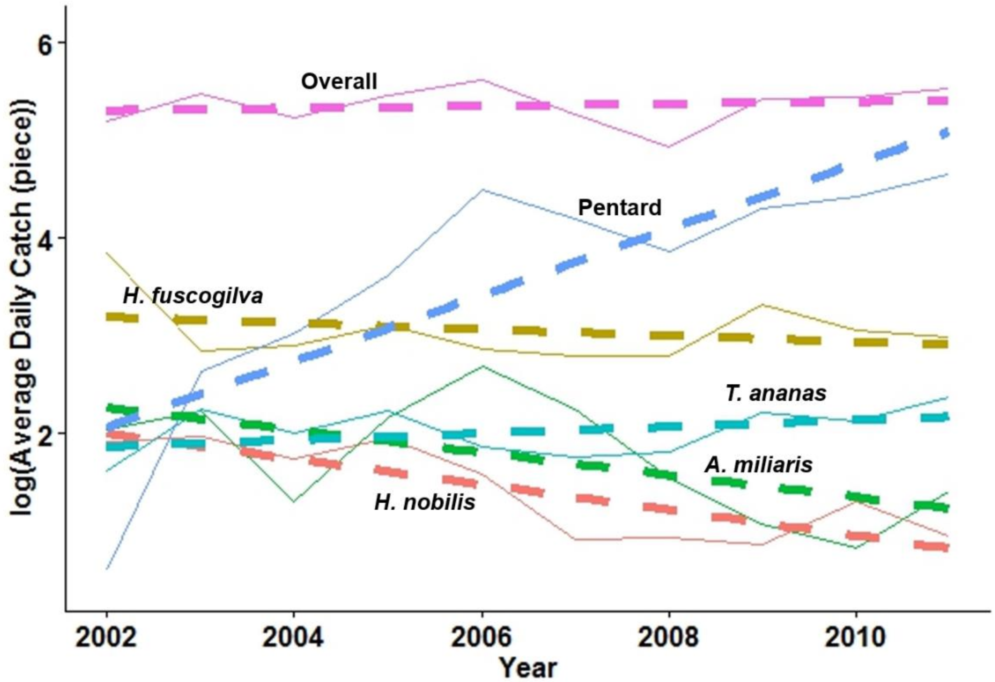


Figure 3.10. Yearly change in average daily catch per unit effort (CPUE) for each species are drawn in solid line. CPUE is logged to fit linear regression line. Dotted line indicates each species' fitted linear regression. Pentard, *T. ananas*, and overall CPUE showed significant increase (p<0.01), whereas H. *nobilis* and *A. miliaris* showed significant decline (p<0.01). *H. fuscogilva* did not show significant change in CPUE (p=0.57).

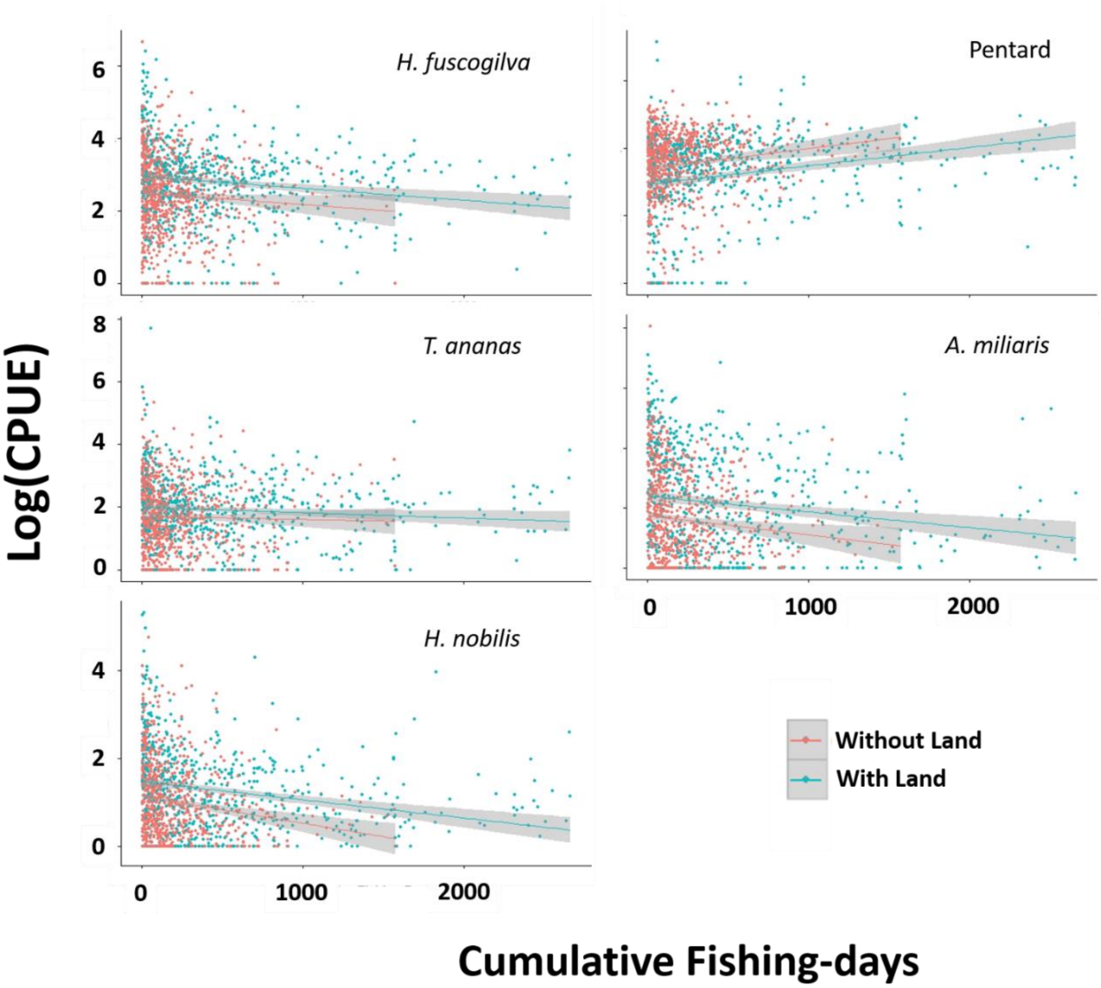


Figure 3.11. Depletion model plotting monthly CPUE against corresponding cumulative fishing effort in each grid cell. Blue indicates grid cells with land and red indicates grid cells without land. Shaded area shows standard error of linear regression. The exponential rate of change in CPUE for each species are as followed: *A. miliaris*, -0.0005/fishing-days ($p<0.01$); *H. nobilis*, -0.0005/fishing-days ($p<0.01$); *H. fuscogilva*, -0.0003/fishing-days ($p<0.01$); *T. ananas*, -0.0002/fishing-days ($p=0.02$); and Pentard, 0.0005/fishing-days ($p<0.01$).

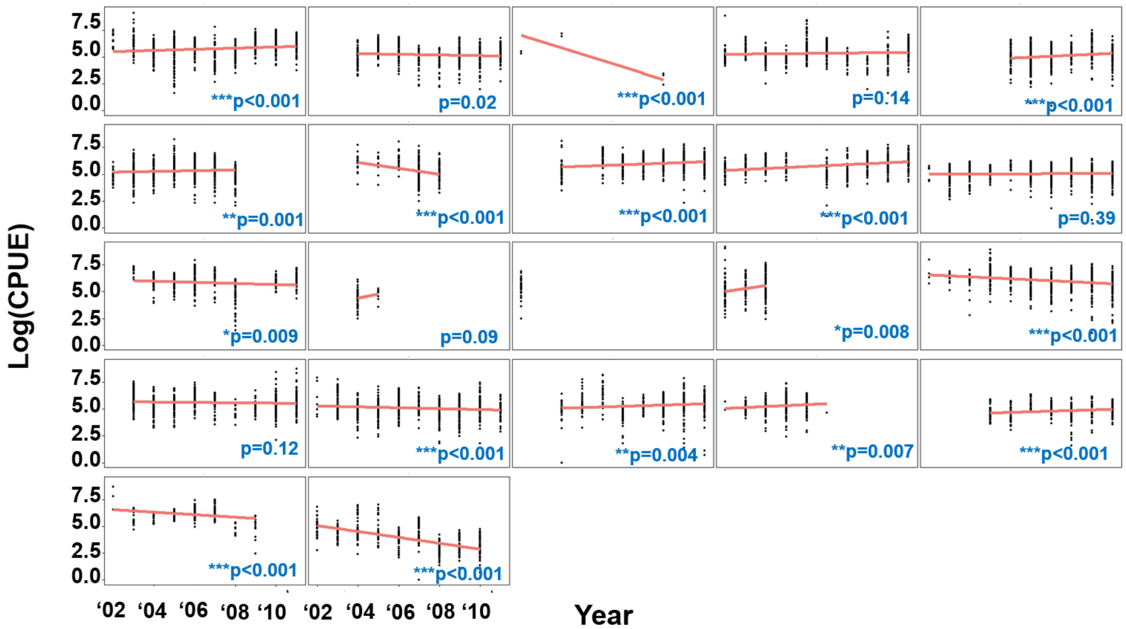


Figure 3.12. Trends in CPUE by vessel. Each graph shows average daily CPUE (pieces/day) trend for each vessel. Black dots are the daily CPUE for each year and red lines depict trends. P-value for least-squares linear regression of CPUE by year for each vessel, with with Bonferroni correction ($\alpha_{critical} = 0.002$).

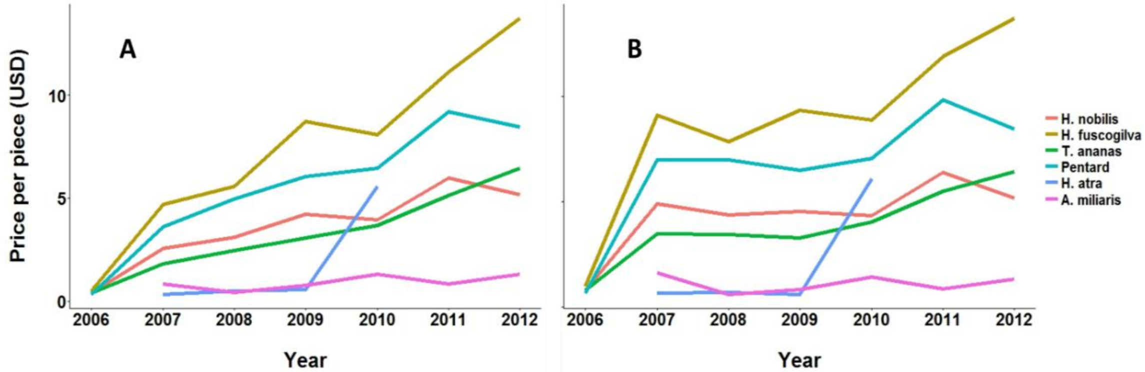


Figure 3.13. The two panels both show export price for each sea cucumber species in Beche-de-mer form between 2006 and 2012 with one showing nominal export price (A) and the other showing export price adjusted in 2012 consumer price index (B).

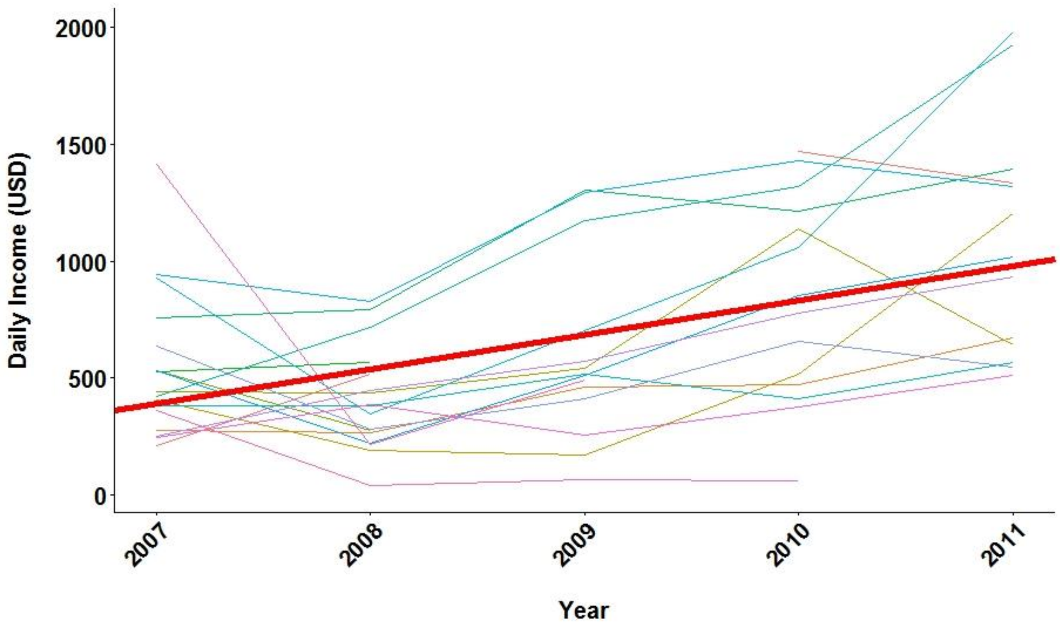


Figure 3.14. The average daily gross income change (adjusted for inflation) for each vessel based on haorbor price from 2006 to 2011 in USD. Pastel colored line represents each vessel and red bold line represents the overall increase in income.

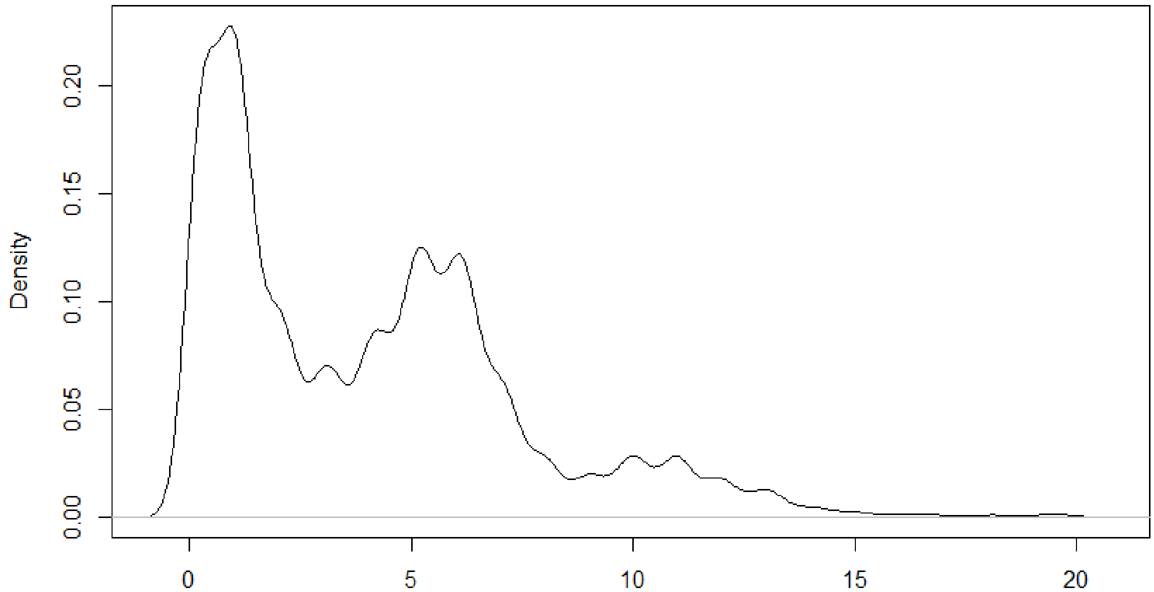


Figure 3.15. Density plot of vessel speed (in knots) recorded from VMS. Each prominent peak was used to define the following fishing activity: vessels fishing (<3 knots), searching (3-7 knots), and steaming/transiting (>7 knots).

CHAPTER IV

ESTIMATING LOCAL RECRUITMENT RATES AND CARRYING CAPACITY OF WHITE TEATFISH (*HOLOTHURIA FUSCOGILVA*) USING A HIERARCHICAL, SPATIALLY EXPLICIT SURPLUS PRODUCTION MODEL

To be submitted to:

Koike, H., Brodziak J., Chang Y.J. (2017). Estimating local recruitment rates and carrying capacity of white teatfish (Holothuria fuscogilva) using a hierarchical, spatially explicit surplus production model. Fish and Fisheries.

Abstract

Hierarchical, spatially explicit surplus production model was created to conduct a multi-area fisheries stock assessment of *Holothuria fuscogilva,* which incorporated bio-physical information, fishery, and in-situ observational data sets. The model demonstrated that this production model can provide simple yet useful life history parameters, while providing an ecosystem approach to stock assessment by accounting for bio-physical factors (e.g. depth). The parameters estimated confirmed extremely low recruitment rate of *Holothuria fuscogilva*, suggesting recruitment overfishing of this stock. The model tracked regional catch data relatively well by approximating local harvest rates between high-abundance and low-abundance areas. We used these results to investigate and discuss the implications of using spatially aggregated stock assessments for fisheries in which the distribution of both the population and fishing vary over space and time.

Introduction

Despite the collapse of many sea cucumber fisheries around the world, overexploitation continues (Anderson et al. 2011, Toral-Granda et al. 2008). Sea cucumbers are particularly vulnerable to overfishing since they have high commercial values (Purcell et al. 2012), are easy to catch (Bell et al 2008), slow growing, and have highly variable recruitment (Uthicke et al. 2004). Populations often show little recovery once they are fished down below a critical population size due to the Allee effect (Friedman et al 2011, Uthicke et al. 2004).

Despite the high demand and the volatile nature of the fishery, much of the life history parameters necessary for sustainable management of sea cucumbers remains unknown. For instance, there have been numerous studies on reproduction and larval of sea cucumbers (Conand 1993, Conand 2008, Kinch et al. 2008), but there are no reliable estimates of adult recruitment rates. Mortality rates and carrying capacity has been estimated for juvenile sea cucumbers in aquaculture settings (Ramofafia et al. 1997, Wiedemeyer 1994), but estimates do not exist for these parameters under natural conditions. Growth rates has been studied through conventional tagging (Conand 1990), genetic tagging (Uthicke and Benzie, 2002), and modal progression analysis (Shelley 1985). However negative growth can result from unfavorable environmental conditions, making it difficult to obtain reliable estimates of growth and mortality rate using traditional growth curves (Skewes et al. 2014).

Stock assessment models allow life history parameters (e.g., growth, mortality, recruitment, etc.) to be estimated from fishery data, but these fisheries-dependent data are virtually non-existent for sea cucumber fisheries. One of the main reason for the lack of stock assessments in sea cucumber fisheries is because these fisheries are usually short-lived (Anderson et al. 2011). Another reason for these fisheries not being properly assessed is a typical problem of many small-scale tropical fishery where reliable fishery data is difficult to collect due to: 1) fishing grounds encompassing heterogeneous habitats, 2) fishermen targeting multiple species that are often grouped when recorded, 3) multiple landing sites diffused along the coast, and 4) operations carried out using multiple gear types, making standardization difficult.

The sea cucumber fishery in the Seychelles is one of the few that is well managed and has lasted for more than two decades (Aumeeruddy and Skews 2005). All the landings get exported to Asian market, and is responsible for about 0.3% of the country's GDP. The fishery does not have the same problems of many other fisheries in that a single harvest method is employed (SCUBA) and fishing effort is somewhat consistent, with four divers allowed per vessel. The operation has minimal bycatch since fishermen collect just their target species. Additionally, fishers record their daily catch by species and operation area by grid cell allowing us to examine differences in catch by habitat (Fig. 1). No other sea cucumber fishery has been recorded at this level of detail. This Seychelles case provides a rare opportunity to create a spatially explicit surplus production model for a sea cucumber fishery, which allows us to estimate critical management parameters such as the adult recruitment rate and carrying capacity. Surplus production models have been criticized for their inability to account for variable recruitment and differences in cohort strength, which has recently led to the use of age-structured models (Carruthers et al. 2011). However, an age-structured model was not suitable for assessing sea cucumber stocks since reliable growth rates cannot be calculated due to difficulties in aging them and their occasional negative growth (Skewes et al. 2014, Uthicke et al. 2004).

Catch data from the Seychelles sea cucumber fishery allowed us to create spatially explicit production model that accounted for the spatial variation in fishing effort and catch. Spatially explicit models allow bio-physical information such as depth, habitat, pollution, and oceanographic conditions to be included directly into the stock assessment model. Another feature of spatially explicit models is that they allow us to account for spatially expanding fisheries. Spatial expansion has been observed in rapidly developing fisheries, including sea cucumber fisheries (Eriksson and Byrne 2015). Spatial expansion often masks the overall decline in catch per unit effort (CPUE) since new areas will have higher catch rates despite the fact that catch rates have declined in established fishing areas. Therefore, not accounting for spatial expansion of a fishery can lead to hyperstability in stock assessment, where managers get a false sense of stable catch (Erisman et al. 2011). Hyperstability is a problem in fishery since it delays the detection of stock decline and management intervention for recovery.

In addition to detailed fishery logbooks, the Seychelles has conducted two fishery-independent dive surveys to assess their stock status; one in 2004 and another from 2011 to 2013. Such fishery-independent survey data can be used to improve parameter estimates in stock assessment models, or as a direct source of stock assessment since they can provide an unbiased index of stock abundance (Gunderson 1993). However, this information was often not integrated into stock assessment models until recent improvements in computing power and the evolution of Bayesian statistics. A Bayesian approach utilizes permutation methods to fit model parameters, and allows direct estimates of parameter uncertainty that are easy to interpret and appropriate for risk analysis (Brodziak and Ishimura 2011). This approach also allows one to source more than one observation data set simultaneously when fitting the parameters. Using this approach, we combined the Seychelles two biological survey data sets to the stock assessment model to improve the estimate of annual stock size and parameters for our production model.

Another strength of a Bayesian approach is that it can account for different levels and scales of components through hierarchical modeling (Clark and Gelfand 2006). This means that models can reflect the bio-physical information at different scale. The Seychelles sea cucumber fishing grounds have areas that include islands, as well as those without. Since sea cucumbers are thought to have better growth with more terrigenous inputs (Mercier et al. 2000, Slater et al. 2010), we used hyper-priors so that the large scale bio-physical information (presence/absence of land) could be used to influence the local parameters (each grid cell's growth rate and carrying capacity).

Ten species (*Holothuria nobilis, H. fuscogilva, H. scabra, H. lecanora, Thelenota ananas, Actinopyga mauritiana, A. echinitis, A. lecanora, A. miliaris*, and an undescribed species "Pentard") are currently listed as commercially exploited for the export market (Aumeeruddy and Payet 2004, Aumeeruddy and Conand 2007). Shifts in target species has been noticed over the years, where earlier fishery targeted mainly *H. nobilis*, *H. fuscogilva*, and *A. miliaris*, whereas later years targeted *H. fuscogilva*, Pentard, *T. ananas*, and *H. atra* (Chapter 2, Koike et al. in prep.). We selected *H. fuscogilva* (locally called white teatfish) as our model species since it has been targeted consistently throughout the years.

This work describes the first spatially explicit, hierarchical production model for a sea cucumber fishery known to date. This model can predict the spatial distribution of the stock, account for spatial expansion of the fishery and bio-physical factors, while also using more than one data source to improve its parameter estimates. We modeled the population dynamic of the white teatfish from 2002 to 2011, and used this model to estimate much needed parameters for the development of sustainable ecosystem-based sea cucumber fishery management.

Materials and Methods

Data Collection

Fishery catch data for assessing white teatfish was taken from fishery logbooks collected by the Seychelles Fishing Authority (SFA) from 2002 to 2011. Fishing ground expands over Mahe plateau, Amirantes islands, Farquhar island groups, and Aldabra islands and is divided into 27km by 27km grid. Catch data are reported for each grid cell (Fig. 4.1). Grid cells without any fishing activities were excluded from the analysis.

Estimates of standardized commercial fishery CPUE were calculated by taking the mean reported daily catch for all vessels for each year T, for each grid j ($I_{T,j}$). Movement of sea cucumbersamong areas were not considered due to the sedentary nature of these species (Toral-Granda et al. 2008). For fishery-independent data, we used the biological surveys conducted in 2004 (Aumeeruddy et al. 2005) and 2011 (Chapter 1, Koike et al. in prep.). Density was estimated based on depth, and abundance was calculated for each fishing grid cell.

Model Description

The stock assessment model was programmed and compiled using R 3.2.5 (R Core Team

2015), JAGS 4.2.0 (Plummer 2004), and rjags 4-6 (Plummer 2013). The underlying population dynamics model was a power function surplus production model modified by Pella & Tomlinson (1969). We utilized data from each fishery reporting grid cell to account for spatial variation. Each grid cell was also assigned as to whether land was present or not to inform the hyper-prior (Fig. 4.1). This was done since CPUE was significantly higher from the areas with land vs. without land (Chapter 2).

The model incorporated the biomass dynamics of each grid cell to predict spatial stock structure. We used Bayesian state space models to account for the non-equilibrium of the stock. Additionally, we used process error to incorporate stochastic variation into the biomass dynamics parameters, and used observation error terms to relate the observed to the predicted CPUE. We used another observation error term to relate the estimated stock size from the biological surveys from 2004 and 2011 to the predicted stock size of those respective years. The directed acyclic graph (DAG) for the model is available in appendix A.

The surplus production model modified by Pella-Tomlinson (1969) has an annual time step (eq 1).

$$B_{T,j} = B_{T-1,j} + R_j * B_{T-1,j}\left(1 - \left(\frac{B_{T-1,j}}{K_j}\right)^M\right) - C_{T-1,j} \qquad \ldots \text{(eq. 1)}$$

Under this three parameters model, current biomass at each grid cell j ($B_{T,j}$) depends on the previous biomass ($B_{T-1,j}$), catch ($C_{T-1,j}$), intrinsic growth rate (R_j) limited by the presence of land, carrying capacity (K_j) limited by the presence of land, and a production shape parameter (M) for T = 2, …., N (Brodziak 2007). This version of the model was chosen since it includes the shape parameter M so that the growth rate does not have to peak at K_{50}. We rewrote this model into equation 2 by reparametrizing $B_{T,j}$ in terms of the proportion of carrying capacity P ($P = B/K$) following methods from Brodziak (2007) (eq 2).

$$P_{T,j} = P_{T-1,j} + R_j * P_{T-1,j}\left(1 - P_{T-1,j}^{M}\right) - \frac{C_{T-1,j}}{K_j} \quad \dots \text{(eq 2)}$$

This was done to improve the efficiency of the Markov Chain Monte Carlo algorithm since it speeds up the mixing process of the Gibbs sampler (Meyer and Millar 1999). Gibbs sampler is a special case of the Metropolis-Hastings algorithm (Metropolis et al., 1953; Hastings, 1970), and one of the most widely used algorithms for simulating Markov chains (Lunn et al. 2013).

The population in each grid cell was limited by a carrying capacity, which was the initial "unfished" size of the population in that grid cell. Each grid cell's carrying capacity (K_j) and growth rate (R_j) were grouped into land present area and land absent area, defined by the hyper-prior to account for the productivity differences in areas with and without terrigenous input.

CPUE was used as the relative abundance index (I), where it was assumed to be directly proportional to the biomass (eq 3),

$$\mathrm{I}_{T,j} = \mathrm{Q}\mathrm{B}_{T,j} \dots \text{(eq 3)}$$

where $\mathrm{I}_{T,j}$ was the daily CPUE for grid cell j for year T and q was the catchability coefficient. The catchability coefficient Q was assumed constant across all vessels and years since the number of harvest dives were limited by the number of divers, which was capped at four per vessel since 2000. Since we rewrote the production model equation in terms of the proportion of carrying capacity ($\mathrm{P}_{T,j}$) instead of the actual stock size ($\mathrm{B}_{T,j} = \mathrm{K}_j \mathrm{P}_{T,j}$), we rewrote eq 3 into eq 4.

$$\mathrm{QB}_{T,j} = \mathrm{QK}_j \mathrm{P}_{T,j} \quad \ldots \text{ (eq 4)}$$

Additionally, an alternative stock size estimate (S_T) from underwater visual surveys (conducted in 2004 and 2011) was used to verify the model's stock size estimate for those years.

$$\mathrm{S}_{T,j} = \mathrm{K}_j \mathrm{P}_{T,j} = B_{T,j} \quad (for\ T = 2004, 2011) \quad \ldots \text{ (eq 5)}$$

The spatial distribution of the stock for each grid cell was based on the depth distribution modeled from fishery-independent survey data (Chapter 2).

Observation Error for CPUE

The observed CPUE dynamics were subject to natural fishing operation variation that was assumed to be lognormally distributed. The observation errors were distributed as $\upsilon_T = \mathrm{e}^{V_T}$ where the V_T are independent and identically distributed (iid) normal random variables with zero mean and precision τ_1, which is $1/\sigma^2$ (JAGS uses τ (precision) instead of σ (standard deviation) to define a normal distribution). Given the lognormal observation errors, the observation equation for each annual period indexed by T = 1, …, N and each grid cell indexed by j = 1, …, J was:

$$I_{T,j} = qK_j P_{T,j} * \upsilon_T \ \ldots \text{(eq 6)}$$

This specified the general form of the observation error likelihood function $p(I_{T,j}|\theta)$ for each fishing event through time.

Observation Error for Biological Survey Estimate

The stock size estimates from the biological surveys were subject to natural sampling variation that was assumed to be lognormally distributed. The observation errors were distributed as $\varphi_T = e^{\phi_T}$ where the ϕ_T are independent and identically distributed (iid) normal random variables with zero mean and precision τ_2. Given the lognormal observation errors, the observation equation for each grid cells indexed by j = 1, …, J was:

$$S_{T,j} = K_j P_{T,j} * \varphi_T \ \ (for\ T = 2004, 2011) \ \ \ldots \ \text{(eq 7)}$$

This specified the general form of the observation error likelihood function $p(S_{T,j}|\theta)$ for biological surveys in 2004 and 2011, respectively.

Process Error for Stock Dynamic

The process error related the observed dynamics of the sea cucumber stock to the deterministic process dynamics (eq. 2), which was subject to fluctuations in many factors such as life history parameters, stochastic events, and inter/intra-specific interactions. Since natural variation is a multiplicative combination of many factors, the process error terms were assumed to be independent and log normally distributed random variables $\eta_T = e^{U_T}$, where U_T was a normal random variable with mean 0 and precision τ_3.

The state equations defined the stochastic process dynamics by linking the predicted stock size states to the observed catches, and estimated population dynamics parameters. Assuming multiplicative lognormal process errors, the state equations for the initial time period (T=1) and subsequent periods (T>1) were:

$$P_{1,j} = C * \eta_1$$

$$P_{T,j} = \left(P_{T-1,j} + R_j * P_{T-1,j}\left(1 - P_{T-1,j}^{M}\right) - \frac{C_{T-1,j}}{K_j}\right) * \eta_T \quad \text{............(eq. 8)}$$

where C was the best guessed proportion for the initial year. These coupled state equations set the conditional prior distribution for the proportion of carrying capacity, $p(P_{T,j})$, in each time period (T) and grid cell j, conditioned on the proportion in the previous period.

Prior Distributions

Under the Bayesian paradigm, prior distributions were employed to quantify existing knowledge, or the lack thereof, or the likely value of each model parameter (Brodziak 2007). For the production model, the model parameters consisted of the carrying capacity (K), the intrinsic population growth rate (R), the shape parameter (M), the catchability coefficient (Q), and the annual stock size as a proportion of carrying capacity (P). Hyper-priors (K_α, K_τ) were used to define a "global" distribution of K based on the presence or absence of land. Auxiliary information was incorporated into the formulation of the prior distributions when it was available.

Prior and hyper-prior for carrying capacity

The prior distribution for the carrying capacity $p(K_j)$ for each grid cell j was chosen to have a lognormal distribution with mean (μ_{K_j}) and precision (τ_{K_j}) parameters. Precision parameters were used instead of variance to describe the distributions for normal and log normal distributions due to JAGS' coding requirement ($\tau = 1/\sigma^2$).

$$p(K_j) = \sqrt{\frac{\tau_{K_j}}{2\pi}} * \frac{1}{K_j} \exp(-\frac{\tau_{K_j}\left(log(K_j)-\mu_{K_j}\right)^2}{2}) \ldots \text{(eq. 9)}$$

The mean parameter (μ_{K_j}) was set to be dependent on the hyper-prior ($K_{\alpha,I}$) and precision parameter (τ_{K_j}) was set to be dependent on the hyper-prior ($K_{\tau,I}$), respectively. Hyper-priors were grouped by the presence/absence of land (I).

The hyper-prior distribution $p(K_{\alpha,I})$ for mean K parameter (μ_{K_j}) was a normal distribution with mean (μ_{K_α}) and precision parameters (τ_{K_α}).

$$p(K_{\alpha,I}) = \sqrt{\frac{\tau_{K_{\alpha,I}}}{2\pi}} * \exp\left(-\frac{\tau_{K_{\alpha,I}}\left(K_{\alpha,I}-\mu_{K_{\alpha,I}}\right)^2}{2}\right) \ldots \text{(eq. 10)}$$

The mean $K_{\alpha,I}$ parameter ($\mu_{K_{\alpha,I}}$) was set at 15.3, which makes the mean K parameter for each grid cell ($\mu_{K,j}$) 15.3 as well. This allowed the carrying capacity (K_j) to be 100 times the mean total landing record for a grid cell. The precision parameter ($\tau_{K_{\alpha,I}}$) was set to achieve a CV as half of $K_{\alpha,I}$, $\mathrm{CV}\left[K_{\alpha,I}\right] = 1/(\mu_{K_{\alpha,I}}\sqrt{\tau_{K_{\alpha,I}}}) = 0.5$. This ensured enough flexibility to estimate different carrying capacity for regions with and without terrigenous input.

The hyper-prior distribution $p(K_{\tau,I})$ for precision K parameter (τ_{K_j}) was a normal distribution with mean ($\mu_{K_{\tau},I}$) and precision parameters ($\tau_{K_{\tau},I}$).

$$p(K_{\tau,I}) = \sqrt{\frac{\tau_{K_{\tau,I}}}{2\pi}} * \exp\left(-\frac{\tau_{K_{\tau,I}}\left(K_{\tau,I}-\mu_{K_{\tau,I}}\right)^2}{2}\right) \text{ … (eq. 11)}$$

The K_τ mean parameter (μ_{K_τ}) was set at 4.48, which makes the K precision parameter (τ_{K_j}) 4.48 as well. This allowed the carrying capacity for each grid cell (K_j) to vary by half of its value, $\mathrm{CV}[K_j] = \sqrt{\exp(1/\tau_{K,I}) - 1} = 0.5$. The precision parameter ($\tau_{K_{\tau,I}}$) was set to achieve a CV that was half of K_τ ($\mathrm{CV}[K_{\tau,I}] = 1/(\mu_{K_{\tau,I}}\sqrt{\tau_{K_{\tau,I}}}) = 0.5$). This ensured enough flexibility to estimate different precision parameter of carrying capacity for region with and without terrigenous input.

Prior for intrinsic growth rate

The prior distribution for the intrinsic growth rate $p(R_j)$ was chosen to be a lognormal distribution with mean (μ_{R_j}) and precision (τ_{R_j}) parameters.

$$p(R_j) = \sqrt{\frac{\tau_{R_j}}{2\pi}} * \frac{1}{R_j} \exp\left(-\frac{\tau_{R_j}\left(log(R_j)-\mu_{R_j}\right)^2}{2}\right) \text{… (eq. 12)}$$

Since the growth rate parameter did not converge, we did not assign hyper-priors for this distribution. The mean parameter (μ_{R_j}) was set to be -10, which was the growth rate estimated from the non-hierarchical homogenous area model. The precision parameter (τ_{R_j}) was set at 4.48, which was set to achieve a CV for half of R_τ, $\mathrm{CV}[R_\tau] = 1/(\mu_{R_\tau}\sqrt{\tau_{R_\tau}}) = 0.5$. This ensured enough flexibility to estimate different precision parameters of growth rates for regions with and without terrigenous input.

Prior for production function shape parameter

The prior distribution for the production function shape parameter $p(M)$ was chosen to be a gamma distribution with shape parameter α and a rate parameter β, which is an inverse scale parameter (β = 1/θ):

$$p(M) = \frac{\beta^{\alpha} M^{\alpha-1} e^{-\beta M}}{\Gamma(\alpha)} \ldots \text{(eq. 13)}$$

The value of the shape and rate parameters were set to α = β = 2. This makes the mean parameter of $p(M)$ to be $\mu(M) = 1$, which corresponds to the M in the symmetric version of Schaefer production model. This choice also gave the shape parameter (M) to have CV of 71%, giving sufficient flexibility to estimate a nonsymmetrical production function if needed.

Prior for catchability

The prior for catchability $p(Q)$ was chosen to be a non-informative uniform distribution with minimum (a) and max (b) parameters.

$$p(Q) = \frac{1}{12} * (b-a)^2 \ \ldots \text{(eq. 14)}$$

Q was set to range between 0 to 1 since that was the range limit of catchability.

Prior for error variances

Priors for the CPUE observation error precision $p(\tau_1)$, biological survey observation error precision $p(\tau_2)$, and process error precision $p(\tau_3)$, were chosen to have Jeffrey prior distributions (Lunn et al. 2013). Jeffrey prior is one of the common non-informative priors since inferences become scale invariant when used on scale parameters, such as variance and precision. A gamma distribution with very small shape and rate parameter approximates Jeffreys prior distribution, thus we set our prior to a gamma distribution with shape and rate parameters set to 0.001 and 0.001, respectively.

Priors for proportions of carrying capacity

Prior distributions for the time series of biomass in proportion to carrying capacity, $p(PT)$, are determined by the lognormal distributions specified in the process dynamics. The mean proportion of carrying capacity for the initial year of 2002 for each grid ($P_{1,j}$) was set to 50% of the carrying capacity. This was to account the fact that Seychelles sea cucumber fishery was fully developed by 2002 and thus we considered the stock to be somewhat depleted.

Posterior distribution

The joint posterior distribution of the *H. fuscogilva* production model needs to be sampled to make inferences about the estimates of the model parameters. The posterior distribution $p(\theta|D)$ was proportional to the product of the prior distributions of the parameters (K, R, M, Q, M, and errors) and the likelihood of the CPUE data given all the data sets (catch, CPUE, and biological survey data, noted as D) via Bayes' theorem

$$p(\theta|D) \propto p(K_a)p(K_\tau)p(K)p(R)p(M)p(Q)p(\eta)p(\upsilon)\mathrm{p}(\varphi)$$
$$\times \prod_{j=1}^{J}\prod_{T=1}^{N} p(P_{j,T}) \prod_{j=1}^{J}\prod_{T=1}^{N} p(I_{j,T}|\theta) \prod_{j=1}^{J}\prod_{T=2004,2011} p(S_{j,T}|\theta) \qquad \ldots \text{(eq. 15)}$$

Parameters for this model were estimated by generating a large number of independent samples from the posterior distribution. In our case, Marcov chain Monte Carlo (MCMC) simulation using Gibbs sampling was conducted using the JAGS software 4.2.0 (Plummer 2004) and rjags package 4-6 (Plummer 2013), which allowed us to set the initial conditions, perform the MCMC calculations, and summarize the results.

MCMC simulations were conducted in two chains of 400,000 samples. A burn-in period eliminated 100,000 samples from each chain to remove any dependence of the MCMC samples on the initial conditions. Next, each chain was thinned by 100 to reduce autocorrelation, and every 100$^{\text{th}}$ sample was used for inference. As a result, 4,000 samples from the posterior were used for summarizing model results.

Convergence of the multiple MCMC chains to the posterior distribution were assessed using Gelman-Rubin scale-reduction factors that compare variation in the sampled parameters value within and between chains (Congdon 2007) using Gelman-Rubin convergence diagnostics in the coda package (Plummer et al. 2006) for R (R Core Team 2015).

Additionally, Heidelberger and Welch's stationary test was conducted using the coda package to test for the stability of the chain. These convergence diagnostics were monitored for several key model parameters (regional and grid-scale intrinsic growth rate, regional and grid-scale carrying capacity, production function shape parameter, catchability coefficient, and error variances) to verify convergence of the MCMC chains to the posterior distribution.

Construction of Harvest Control Graph

One of the objectives for this study was to estimate reference points for sustainable management of the Seychelles sea cucumber fishery. The reference points B_{MSY} (stock size that produces maximum sustainable yield (MSY)), H_{MSY} (harvest rate that produces MSY), and associated MSY were estimated using the production model parameters estimated. The equations (eq.3 – eq.5) described in Brodziak and Ishimura (2011) were modified and used to estimate these reference points. This method was preferred over the 20 ~ 30% of virgin biomass (Hilborn 2010) or fitting through a yield per recruit model (Maunder 2008), since there was too little information on virgin stock size or age-based fecundity for sea cucumbers.

For the discrete-time power function model, the stock size that produced MSY (B_{MSY}) was

$$B_{MSY} = \sum_{j=1}^{J} K_j (M+1)^{\frac{-1}{M}} \quad \ldots \text{(eq. 16)}$$

The corresponding harvest rate that produced MSY (H_{MSY}) was

$$H_{MSY} = \sum_{j=1}^{J} R_j \left(1 - \frac{1}{M+1}\right) \dots \text{(eq. 17)}$$

and the associated value of MSY was

$$MSY = \sum_{j=1}^{J} R_j \left(1 - \frac{1}{M+1}\right) * K_j (M+1)^{\frac{-1}{M}} \dots \text{(eq. 18)}$$

With these reference points, we created a harvest control rule graph to visualize the status of the stock compared to sustainable stock size. We set the target stock size at 1.3*B_{MSY} to account for the natural population fluctuation and uncertainty in estimating B_{MSY} (Froese and Proelß 2010). We limited stock size at 0.5*B_{MSY}, where 0.5 is a factor reflecting the expectation that a stock fished at optimal fishing pressure (F_{MSY}) would naturally fluctuate around B_{MSY} (Gabriel and Mace 1999, Froese et al. 2011).

Hypothesis Test Using Goodness-of-fit criteria

Model residuals were used to measure the goodness-of-fit for each production models (hierarchical vs non-hierarchical). Residuals for the CPUE series were the log-scale observation errors $\varepsilon_{j,T}$ (Brodziak and Ishimura 2011).

$\varepsilon_{j,T} = \log\left(I_{j,T}\right) - \log(QK_j P_{j,T})$ …(eq. 19)

Using these residuals, we calculated the root mean-squared error (RMSE) of the CPUE fit.

$RMSE = \sqrt{(\varepsilon_{j,T})^2/\sum T}$ … (eq. 20)

Results

Convergence to posterior distribution

The potential scale reduction factor was calculated for the intrinsic population growth rate (R_j), local carrying capacity (K_j), regional carrying capacity ($K_{\alpha,I}$ and $K_{\tau,I}$), production function shape parameter (M), catchability coefficients (q), and error variance parameters ($\upsilon_T, \varphi_T, \eta_T$). For all parameters, the estimated potential scale reduction (psr) values were approximately 1.0 (multivariate psr factor = 1.06), meaning that the MCMC chains had successfully converged to the posterior distribution. Similarly, Heidelberger and Welch's stationary test failed to reject the null hypotheses that MCMC chains were stationary at the 95% confidence level for any of the parameters indicating successful MCMC chain conversion. Lastly, visual inspection of the density plots of the posterior distributions of the intrinsic population growth rate, local carrying capacity, hyper-priors for carrying capacity, production function shaper parameter, catchability coefficients, and error variances indicated that these densities were smooth and unimodal for all parameters indicating successful parameter estimation. Overall convergence diagnostics that were examined indicated that the MCMC samples generated from the production model had numerically converged to the posterior distribution.

Model fits to CPUE

The observed CPUE had a dramatic decline in the initial year, whereas the predicted CPUE showed a more gradual decline (Fig. 4.2a). Predicted overall CPUE (estimated by summing all the predicted CPUE values for each grid cell) was consistently higher than the observed CPUE after 2004 (Fig. 4.2a). CPUE for each grid cell showed a noisier decline than predicted by the model (Figure 4.2b). Examination of the log-scaled residuals indicated that there was a significant increase in residuals over the years ($p<0.01$).

Estimates of model parameters and reference points

The mean local intrinsic population growth rate (R_j) was estimated to be $\overline{\mathrm{R}_J} = 0.00005$ for both areas with or without terrigenous input (Table 4.1). The distribution of growth rates showed no strong spatial pattern. Furthermore, growth rates differed little from grid to grid (Fig. 4.3a). The regional hyper-priors for carrying capacity grouped by area with and without land were 11.03 and 10.52, respectively (Table 4.1). The 95% confidence interval for each regional hyper-prior did not overlap indicating that carrying capacity differed with terrigenous inputs. This was reflected in the local carrying capacity for each grid where mean K for grid cells with land was 66,133 and grid cells without land was 39,443. Interestingly, area with highest carrying capacity was concentrated at the southeast area of the Mahe Plateau. The estimate of the production model parameter (M) was 1.00 indicating that MSY occurs when stock size is at 50% of carrying capacity. For the biological reference points, the mean estimate of B_{MSY} for each grid cell was 33,066 for the grid cells with land and 19,721 for the grid cells without land. The mean estimate of H_{MSY} for both grid cells with land and without land was 0.000025.

Estimates of exploitable stock size and exploitation rate

Estimated total exploitable stock size declined from 2002 to 2011. The model estimated that initial total stock size in 2002 was at MSY, but subsequent stock sizes were below B_{MSY} (but not significantly since B_{MSY} is within 95% confidence interval of estimated stock size) (Fig. 4.4a). Mean H_{MSY} for any grid cell was extremely low for white teatfish, thus mean exploitation rates were above H_{MSY} throughout the years. Furthermore, the exploitation rate increased from 2002 to 2011, especially after 2008 (Fig. 4.4b). The spatial distribution of the areas fished above H_{MSY} starts mainly at the southeast part of the Mahe Plateau and expands inwards as years progress (Fig. 4.5). The southern part of the Amirantes Islands were also consistently fished above H_{MSY}.

Discussion

The aim of our study was to develop a hierarchical spatially explicit surplus production model to estimate parameters needed for sustainable management of white teatfish in the Seychelles and to assess its stock status. Overall results suggested that there has been virtually no recruitment of exploitable sized sea cucumbers (extremely low population growth rate) and that the fishery has been fishing down the original stock from 2002. Local stock growth rates did not vary between areas with and without terrigenous input. The model with regional growth rates did not even converge. In fact, the growth rates were so small that the variance between the grid cells was negligible. This result was consistent with reports of the absence in sea cucumber stock recovery after fishery closures in other parts of the world (Uthicke et al. 2004, Friedman et al. 2011). Reproductive studies have shown that teat fish gonads reach sexual maturity during austral summer (Nov-Dec) (Ramofafia et al. 2000). However, juveniles have not been observed in recent years (Uthicke et al. 2004, Chapter 1, Koike et al. in press) indicating low spawning events or recruitment failure. Juvenile mortality is thought to be high (Purcell et al. 2016), and this combined with the low recruitment has resulted in very few individuals surviving to harvestable adult size.

The values of the carrying capacity for each grid cell was estimated to between 39,000 and 66,000 depending on proximity to islands. This value equates to about 0.5 to 1 individual ha^{-1}, which is equivalent to the fished population density in other tropical area (0.5 -3.0 ha^{-1}) (Toral-Granda et al. 2008). This low carrying capacity could be due to the fact that most fishing grounds in Seychelles are deep and may not support high stock densities compared to those observed in the shallow areas. Carrying capacity showed significantly higher values for grid cells adjacent to islands. However, the southeast section of the main Mahe Plateau, which is without land, showed higher carrying capacity than all other areas, indicating that carrying capacity may be driven by other factors.

This high carrying capacity in southeast section could be due to the Seychelles-Chagos upwelling dome that occurs during the north-east monsoon season (Hermes and Reason 2008). This upwelling dome is known to be nutrient rich (Yokoi et al. 2008) and occurs between 5 degrees to 10 degrees of southern latitude (Schott et al. 2002), which encompasses the southeast part of the Mahe plateau but not the northwest part of the plateau. This could explain why northwest section of plateau has lower carrying capacity compared to that of southeast section, although it has similar shallow habitat (Fig. 4.6). Furthermore, white teatfish are thought to spawn during summer (Ramofafia et al. 2000), thus the summer equatorial counter current could carry the egg and planktonic larvae eastwards providing more settling opportunities for larvae in southeast section of the plateau.

The MSY results from the model suggest that the stock has been consistently overfished throughout the years, which has likely resulted in recruitment overfishing. Over-exploitation started from the most productive area, which was the southeast part of the Mahe Plateau, followed by the northeast shallow section of the plateau, and then other shallower habitat areas. This clearly shows that fishermen targeted the productive area with high carrying capacity first before moving to less productive areas. This was also apparent from the fact that areas with low carrying capacity were fished above H_{MSY} in later years, although these areas had the highest chance of being overfished. The Bayesian approach allowed us to be extremely confident (<1 out of 100) that the stock has been fished above H_{MSY} for most areas in 2012.

Extreme low population growth rates indicate that Seychelles' sea cucumber fishery has been fishing down their white teatfish stock over the last decade. Therefore, we suggest that currently, it is nearly impossible to sustainably harvest white teatfish in the Seychelles. Areas with high carrying capacity still had low recruitment rates, indicating that the stock does not have an ability to recover from additional fishing (no grid cells showed sustainable landing above one sea cucumber). Similar result has been determined for black teatfish (*H. whitmaei*) stock in Torres Straits where stock was predicted to decrease even with no catches from Allee effect (Skewers et al. 2014). The fishery has very high monetary value and closing this fishery will likely suffer Seychelles' economy. One possible solution could be a stock enhancement program targeting high carrying capacity area identified form our model (Bell et al. 2008). Total landing in 2011 for white teatfish was ~ 72,000 individuals. Therefore, releasing the number of juveniles that could ensure this number of landing could prevent both stock depletion and fishery closure.

Survival rate of juveniles to adulthood in hatchery is about 13%. If we were to produce 1.5 million young adults (double the amount of current landing), we assume that the fishermen could sustain their current catch. The cost to rear 1.5 million juveniles to be released into the ocean annually is about 1.3 million USD. By releasing the juveniles into the ocean, the grow-out cost can be ignored, thus minimizing the program cost. The white teatfish needs to be at least 18 USD per piece in order to have the hatchery program pay itself. Export price for white teatfish was 13.71 USD in 2012. The market price of sea cucumbers have been steadily increasing globally, with white teatfish price increasing about $0.90 USD annually in the Seychelles from 2002 to 2012 (Chapter 2, Koike et al. in prep.). This indicates that if the fishery could wait another 5 to 10 years, the stock enhancement program cost could be covered by the fishery. However, stock enhancement idea is only viable if the management's interest is in maintaining the fishery or invested in future market growth, since the program is barely breaking even with fishery's total gain. Aquaculture is another option, but the number of participants in fishery will likely decrease since it requires less personnel to run a facility.

The Bayesian approach taken in this study allowed us to easily merge fishery-independent survey data and fishery-dependent logbook data. We believe that creating stock assessment models that fully utilize all available data without losing information is critical since data collection is expensive and difficult to collect, particularly in tropical small-scale fisheries. Furthermore, having multiple sources of information greatly reduces the chances of error through verification.

Our study also presented the importance and potential use of spatial information in fishery stock assessments. When fishing effort and catch are logged with spatial information, it enables us to account for spatial expansion of the fishery and differences in habitat, which allow us to explore the spatial variation in model parameters. Most fishermen are reluctant to sharing their fishing locations, but the benefit is well worth the effort to find a spatial scale that is meaningful for analysis and management but coarse enough so that fishermen feel comfortable in sharing this information.

Having spatial information for this fishery also allowed us to examine the interaction with other spatial information (e.g. bio-physical data). Furthermore, a Bayesian hierarchical approach makes our assessment statistically robust in testing if parameters differ by other environmental elements. With more fisheries transitioning to ecosystem-based fishery management (Garcia et al 2005; Christensen and Maclean 2011), parameters that are spatially explicit and used in conjunction with environmental factors are becoming more in demand. Our study successfully demonstrated the use of a hierarchical spatially explicit stock assessment model under an ecosystem-based fishery management framework. Collecting spatial fishery information is financially challenging, capacity tasking, and difficult to get cooperation from fishermen. However, we believe it provides very valuable information that “make sense” biologically and socially. The spatial variability of the growth rate and carrying capacity makes ecological sense, but it has been neglected quite often in fishery model due to difficulty in incorporating. However, we found that it became very simple and straight forward when we used hierarchical Bayesian model and collected spatial fishery information.

Simulation capacity in stock assessment is critical for managers since they can test the effectiveness of their management options before implementing them (Sainsbury et al. 2000). Bayesian models are especially good at this since they account for uncertainty and can provide the probability of effectiveness (Ellison 2004). By being able to measure the uncertainty, different assumptions and management scenarios could be compared with success rate during management strategy evaluation (MSE). Furthermore, by creating a spatially explicit model in our study, we can allow managers to simulate spatial managements options as well. For example, managers could examine the change in landing if fishing pressure was distributed depending on productivity of the area. This makes our model relevant for ecosystem-based MSE (Pelletier and Mahevas 2005, Hill et al. 2007). The weak link to sustainable sea cucumber fishery are: enforcement, stake holder involvement, and communication with fishers (Purcell et al. 2014). Simulation models also allow managers to share their management decision’s effectiveness and likelihood success to stakeholders with clarity, allowing trust and constructive discussions between the two groups.

Short fishing seasons, limited entry to fishery, short list of allowable species and tight enforcement at export points (to prevent black market) are some of the effective management methods to prevent overfishing (Purcell et al. 2013, Purcell et al. 2014). Seychelles’ sea cucumber fishery targets multiple species thus we believe identifying species that have descent recruitment and only allowing the fishery to target those species would be crucial if they are to harvest wild sea cucumber sustainably.

Sea cucumber fishery has been playing a significant role in poverty reduction in developing countries for many years (Kinch et al. 2008). Ease of harvest has also played a role in female participation in often male dominated fishery (Conand and Muthiga 2007). Overfishing has been prominent especially in countries with low human development index due to weak management capacity (Purcell et al. 2013). Seychelles is not the typical case of small-scale sea cucumber fishery since it does have strong management capacity with limited licensing system, and descent enforcement capacity by requiring all fishing vessels to install vessel monitoring system (VMS). However, the fishery is still fragile, and economically and ecologically important. Sea cucumbers are the bioremediators, reducing organic load, redistributing surface sediments, and enhancing productivity of benthic biota through nitrogen excretion, which is crucial in oligotrophic waters such as coral reefs (Purcell et al. 2016). Overfishing of sea cucumbers will lead to reduction in these ecological function, impairing overall marine resource productivity. In order for Seychelles sea cucumber fishery to successfully continue without negative impact to other marine resources, we believe it needs to discuss with stakeholders to either 1) restrict the target species to the ones that have positive recruitment rate (by using models like this study), or 2) enhance high-value stocks that do not have high enough recruitment rate, or 3) do both.

References

Anderson, S.C., Flemming, J.M., Watson, R. and Lotze, H.K. (2011). Serial exploitation of global sea cucumber fisheries. *Fish and Fisheries*, *12*(3), 317-339.

Aumeeruddy R., Skews T. (2005) Resource assessment of the holothurian populations in the Seychelles. *SPC Beche de Mer Information Bulletin*, 21, 19 – 21.

Aumeeruddy R, Skewes T, Dorizo J, Carocci F, Coeur de Lion F, Harris A, Henriette C, Cedras M. (2005). *Resource assessment and management of the Seychelles sea cucumber fishery*. FAO Project Number: TCP/Seychelles/2902(A), 49.

Bell, J. D., Steven W. P., and Warwick, J. N. (2008). Restoring small-scale fisheries for tropical sea cucumbers. *Ocean & Coastal Management* 51, 8, 589-593.

Brodziak, J. and Ishimura, G. (2011). Development of Bayesian production models for assessing the North Pacific swordfish population. *Fisheries Science* 77, 1, 23-34.

Carruthers, T. R., M. K. McAllister, and N. G. Taylor. (2011). Spatial surplus production modeling of Atlantic tunas and billfish. *Ecological applications* 21, 7, 2734-2755.

Christensen, V., and J. Maclean. (2011) *Ecosystem Approaches to Fisheries: a Global Perspective*. Cambridge University Press.

Clark, J. S., and A. E. Gelfand. (2006). *Hierarchical modelling for the environmental sciences: statistical methods and applications*. Oxford University Press on Demand.

Conand, C. and N.A. Muthiga. (2007). *Commercial Sea Cucumbers: a review for the Western Indian Ocean*. WIOMSA Book Series 5, 66pp.

Conand, C. (2008). Population status, fisheries and trade of sea cucumbers in the Indian Ocean. *In*: Toral-Granda V., Lovatelli A., Vasconcellos, M. (eds). *Sea Cucumbers: a Global Review on Fisheries and Trade*. FAO Fisheries and Aquaculture Technical Paper. No. 516. Rome, FAO. pp. 153–205.

Conand, C. (2004). *Advances in sea cucumber aquaculture and management*. No. 463. Food & Agriculture Org.

Conand, C. (1993). Reproductive biology of the holothurians from the major communities of the New Caledonian lagoon. *Marine Biology*, 116: 439–450.

Congdon, P. (2007). *Bayesian statistical modelling (Vol. 704*), John Wiley & Sons.

Ellison, A. (2004). Bayesian inference in ecology. *Ecol Let.*, 7, 509-520.

Eriksson, H. and M. Byrne. (2015). The sea cucumber fishery in Australia's Great Barrier Reef Marine Park follows global patterns of serial exploitation. *Fish and Fisheries* 16, no. 2, 329-341.

Erisman, B. E., L. G. Allen, J. T. Claisse, D. J. Pondella, E. F. Miller, and J. H. Murray. (2011). The illusion of plenty: hyperstability masks collapses in two recreational fisheries that target fish spawning aggregations. *Canadian Journal of Fisheries and Aquatic Sciences*, 68, no. 10, 1705-1716.

Friedman, K., H. Eriksson, E. Tardy, and K. Pakoa. (2011). Management of sea cucumber stocks: patterns of vulnerability and recovery of sea cucumber stocks impacted by fishing. *Fish and Fisheries*, 12, no. 1, 75-93.

Froese, R. and A. Proelß. (2010). Rebuilding stocks until 2015: will Europe meet the deadline? *Fish* *and Fisheries*, 11(2), 194-202.

Froese, R., Branch, T. A., Proelß, A., Quaas, M., Sainsbury, K., & Zimmermann, C. (2011). Generic harvest control rules for European fisheries. *Fish and Fisheries*, 12(3), 340-351.

Gabriel, W. L. and P. M. Mace. (1999). A review of biological reference points in the context of the precautionary approach. *In Proceedings of the fifth national NMFS stock assessment workshop: providing scientific advice to implement the precautionary approach under the Magnuson-Stevens fishery conservation and management act. NOAA Tech Memo NMFS-F/SPO-40* (pp. 34-45).

Garcia, Serge M., and Kevern L. Cochrane. (2005). Ecosystem approach to fisheries: a review of implementation guidelines. *ICES Journal of Marine Science: Journal du Conseil* 62, no. 3, 311-318.

Gunderson, D. R. (1993). *Surveys of Fisheries Resources*. John Wiley & Sons.

Hastings, W. K. (1970). Monte Carlo sampling methods using Markov chains and their applications. *Biometrika*, 57, no. 1, 97-109.

Hermes, J.C. and C.J.C. Reason. (2008). Annual cycle of the South Indian Ocean (Seychelles-Chagos) thermocline ridge in a regional ocean model. *Journal of Geophysical Research: Oceans*, 113(C4). (http://onlinelibrary.wiley.com/doi/10.1029/2007JC004363/full)

Kinch, J., S. Purcell, S. Uthicke, and K. Friedman. (2008a). Population status, fisheries and trade of sea cucumbers in the Western Central Pacific. *FAO Fisheries and Aquaculture Technical Paper*.

Lunn, D., C. Jackson, N. Best, A. Thomas, and D. Spiegelhalter. (2012). *The BUGS Book: A*

Practical Introduction to Bayesian Analysis. CRC press.

Plummer, M., N. Best, K. Cowles and K. Vines. (2006). CODA: Convergence Diagnosis and Output Analysis for MCMC, *R News*, vol 6, 7-11.

Mercier, A., S.C. Battaglene, and J. F. Hamel. (2000). Periodic movement, recruitment and size-related distribution of the sea cucumber Holothuria scabra in Solomon Islands. *Island, Ocean and Deep-Sea Biology*, 81-100.

Metropolis, N., A. W. Rosenbluth, M. N. Rosenbluth, A. H. Teller, and E. Teller. (1953). Equation of State Calculations by Fast Computing Machine. *Journal of Chemical Physics*, 21, 1087-1092.

Plummer, M. (2013). *rjags: Bayesian graphical models using MCMC*. R package version 3.

Plummer, M. (2004). *JAGS: Just another Gibbs sampler*.

Purcell, S. W., A. Lovatelli, and K. Pakoa. (2014). Constraints and solutions for managing Pacific Island sea cucumber fisheries with an ecosystem approach. *Marine Policy*, 45, 240-250.

Purcell, S. W., C. Conand, S. Uthicke, and M. Byrne. (2016). Ecological roles of exploited sea cucumbers. *Oceanography and Marine Biology: An Annual Review* 54, 367-386.

Purcell, S. W., Y. Samyn, and C. Conand. (2012). *Commercially important sea cucumbers of the world.* FAO Species Catalogue for Fishery Purposes No. 6, FAO, Rome.

Ramofafia, C., S. C. Battaglene, J. D. Bell, and M. Byrne. (2000). Reproductive biology of the commercial sea cucumber Holothuria fuscogilva in the Solomon Islands. *Marine Biology*, 136, no. 6, 1045-1056.

Ramofafia, C, T. P. Foyle, and J. D. Bell. (1997). Growth of juvenile Actinopyga mauritiana

(Holothuroidea) in captivity. *Aquaculture* 152, no. 1, 119-128.

R Core Team. (2015). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Sainsbury, K. J., A. E. Punt, and A. D. M. Smith. (2000). Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science: Journal du Conseil*, 57, no. 3, 731-741.

Schott, F.A., M. Dengler, and R. Schoenefeldt. (2002). The shallow overturning circulation of the Indian Ocean. *Progress in Oceanography*, 53(1), 57-103.

Shelley, C. C. (1985). Growth of Actinopyga echinites and Holothuria scabra (Holothurioidea: Echinodermata) in Papua New Guinea. In *Proc. 5th Int. Coral Reef Congr*, vol. 5, 297-230.

Skewes, T., E. Plaganyi, N. Murphy, R. Pascual, and M. Fischer. (2014). *Evaluating Rotational Harvest Strategies for Sea Cucumber Fisheries*. CSIRO.

Slater, M. J., A. G. Carton, and A. G. Jeffs. (2010). "Highly localised distribution patterns of juvenile sea cucumber Australostichopus mollis." *New Zealand Journal of Marine and Freshwater Research*, 44, no. 4, 201-216.

Toral-Granda, V., A. Lovatelli, and M. Vasconcellos. (2008). *Sea cucumbers: a global review of fisheries and trade*. Food and Agriculture Organization of the United Nations.

Uthicke, S., D. Welch, and J. A. H. Benzie. (2004). Slow Growth and Lack of Recovery in Overfished Holothurians on the Great Barrier Reef: Evidence from DNA Fingerprints and Repeated Large-Scale Surveys. *Conservation Biology* 18, no. 5, 1395-1404.

Vasconcellos M. (eds). Sea cucumbers: a global review on fisheries and trade. *FAO Fisheries and*

Aquaculture Technical Paper. No. 516. Rome, FAO. pp. 7–55.

Wiedemeyer, W. L. (1994). Biology of small juveniles of the tropical holothurian Actinopyga echinites: growth, mortality, and habitat preferences. *Marine Biology*, 120, no. 1, 81-93.

Yokoi, T., T. Tozuka, and T. Yamagata. (2008). Seasonal variation of the Seychelles Dome. *Journal of Climate*, 21(15), 3740-3754.

Table 4.1. Mean estimates of production model parameters. For the parameters estimated for the entire stock, 95% confidence interval in parentheses.

	$(\overline{r_j})$	$(\overline{K_j})$	K_alpha	K_tau	M	Q	$B_{MSY,j}$	MSY_j	$H_{j,2006}$
Area with land	5.07*e-05	66,133	11.03 (10.8 ~ 11.2)	6.07 (3.3 ~ 9.5)	1.00 (0.12 ~ 2.87)	0.0007 (0.0006 ~ 0.0008)	33,066	0.8	0.03
Area without land	5.08*e-05	39,443	10.52 (10.4 ~ 10.7)	7.37 (4.7 ~ 10.7)			19,721	0.5	0.10

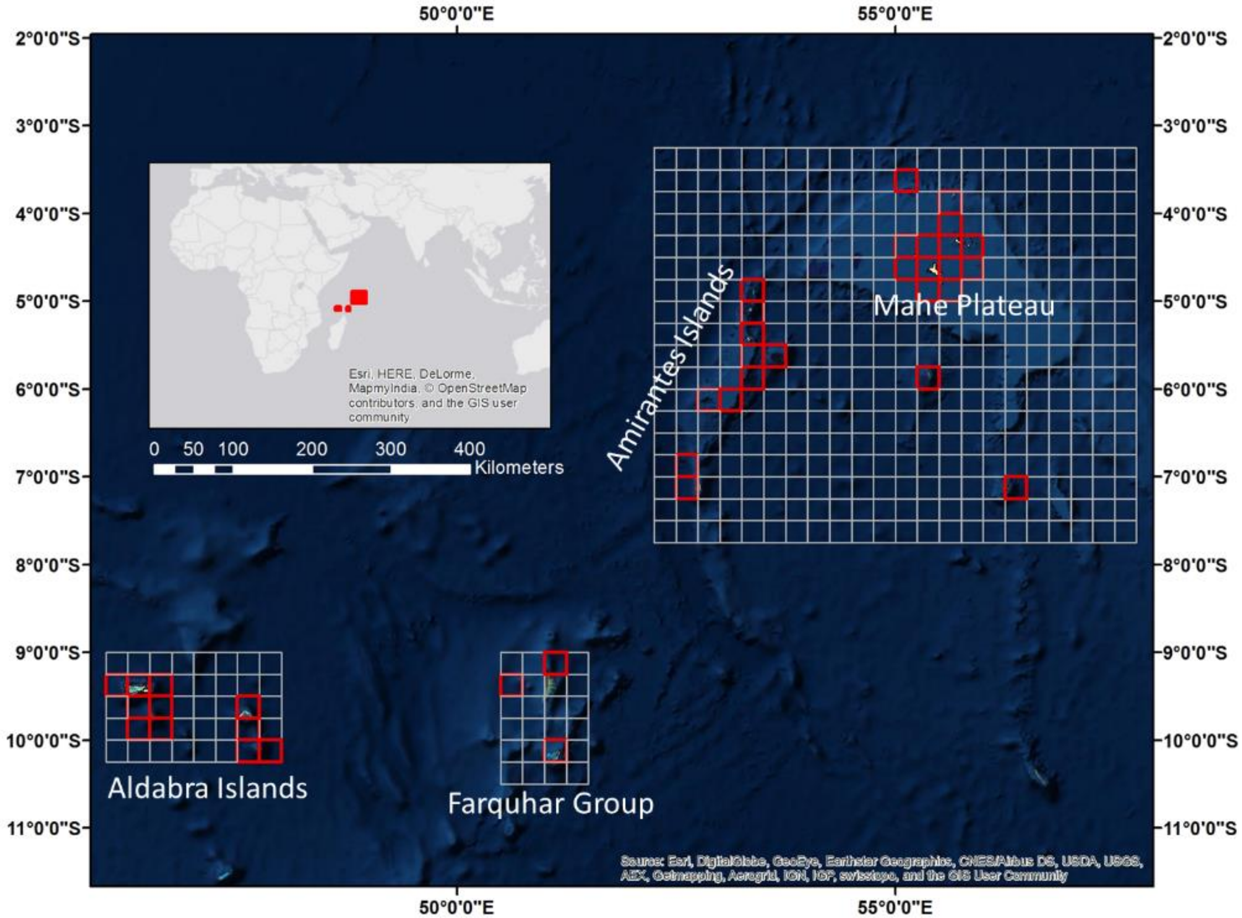


Figure 4.1. Reporting grid for the Seychelles sea cucumber fishing grounds with regional names. Grid cells delineated in red are those with land.

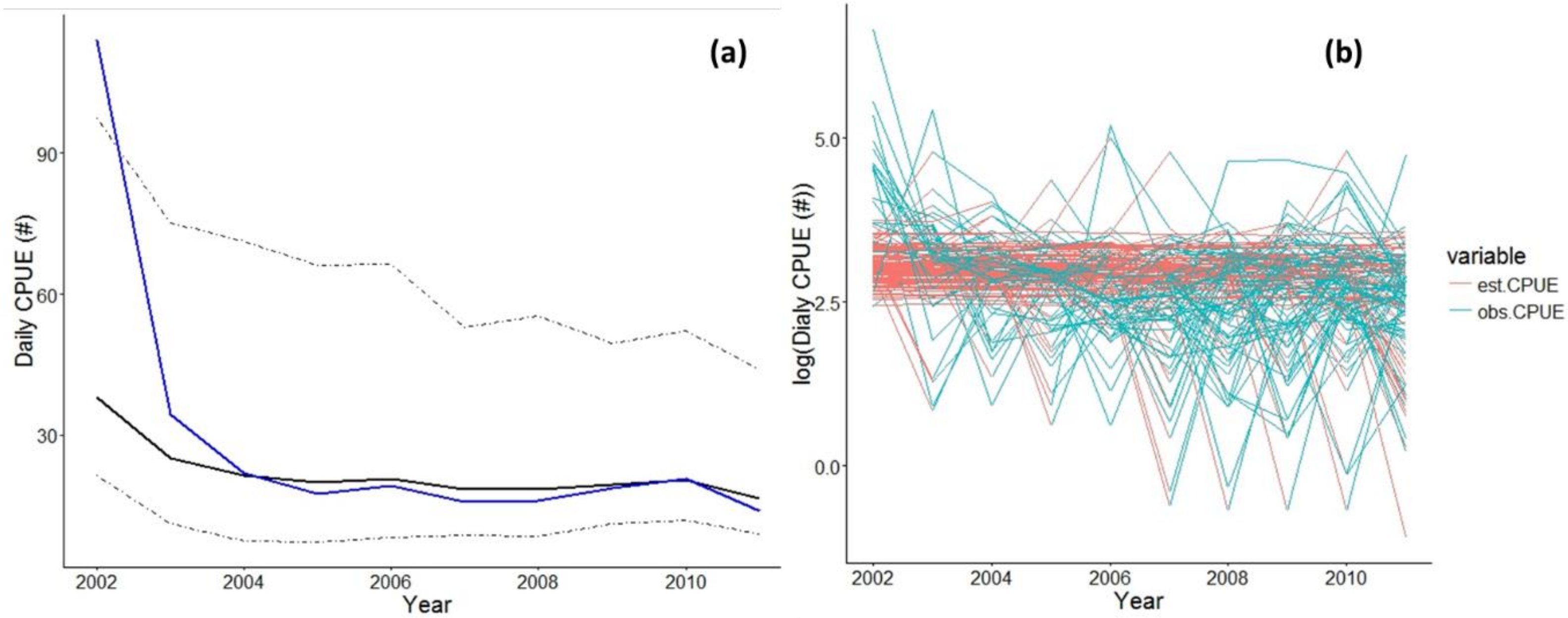


Figure 4.2. **a)** Time series of observed and predicted mean catch per unit effort (CPUE) per grid cell for *H. fuscogilva*. The blue line indicates the observed CPUE and black line indicates the estimated CPUE. The dotted lines are the 95% confidence intervals of the predicted CPUE. **b)** CPUE trend for each grid cell, where blue is the observed local CPUE and red is the predicted local CPUE in logarithm.

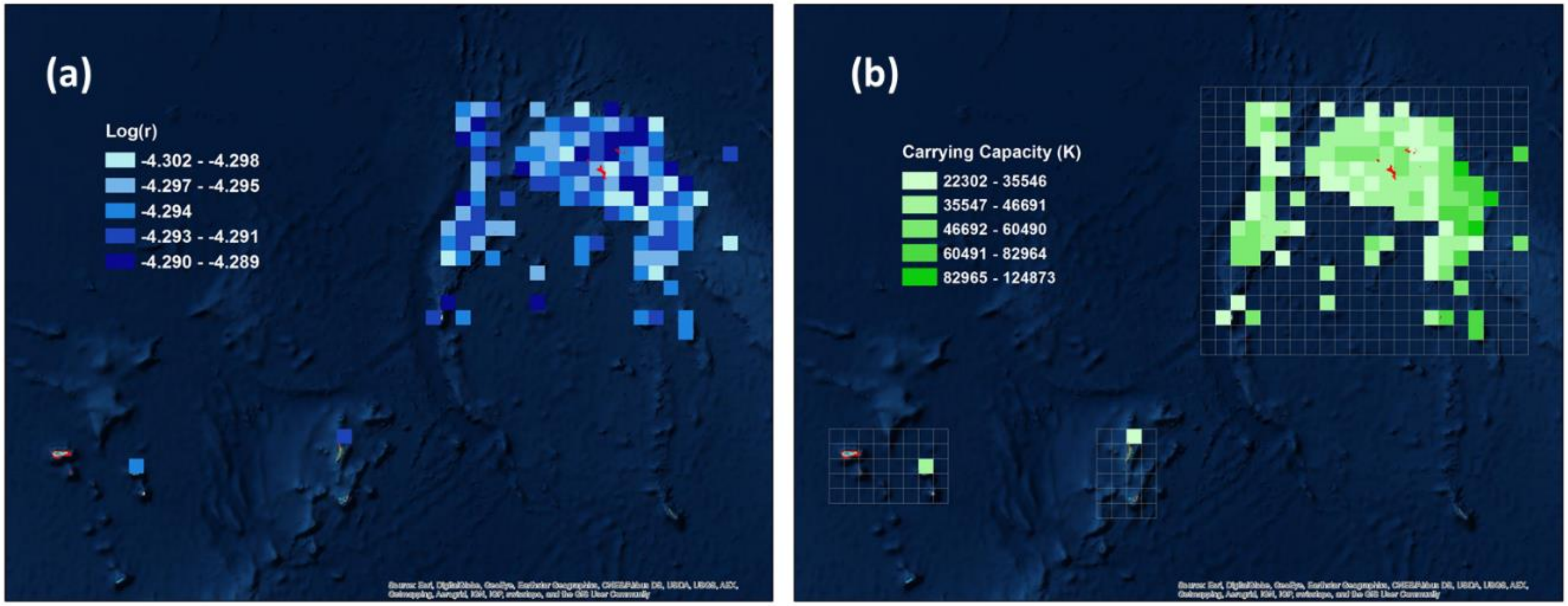


Figure 4.3. A. Spatial distribution of estimated local population growth rate parameter (Log[r]). B. Local carrying capacity (K) for each reporting grid cell. Islands are delineated in red.

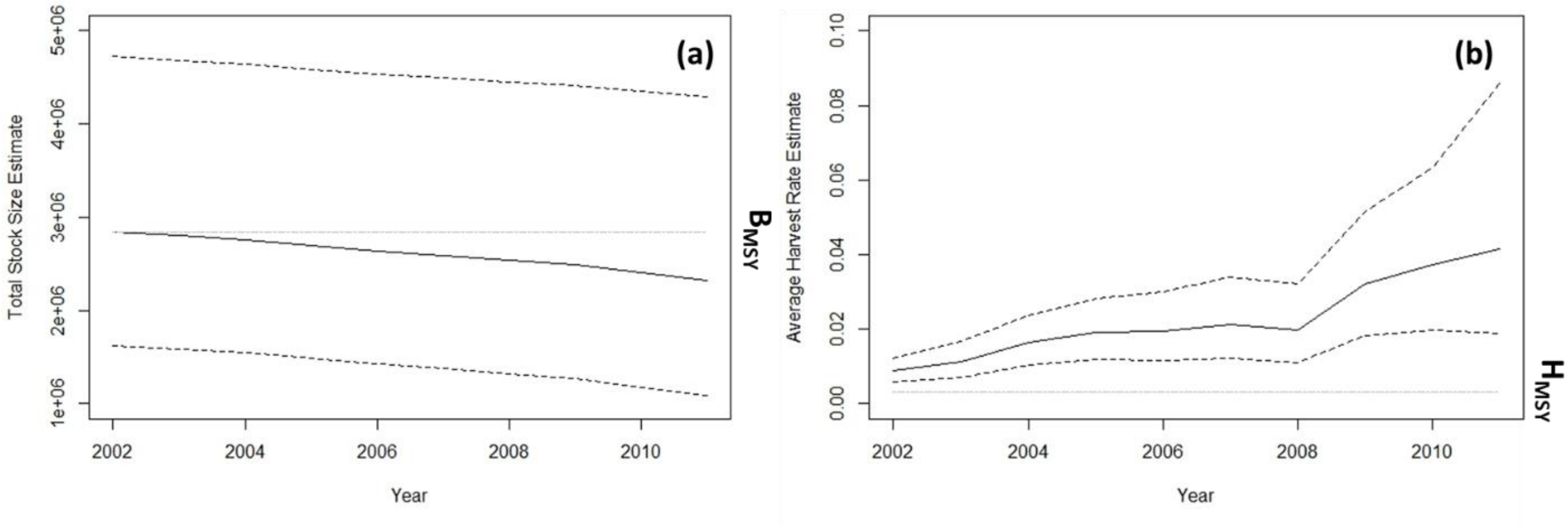


Figure 4.4. A. Trends in total exploitable number of white teatfish in the Seychelles. B. Trends of mean exploitation rate for each reporting grid cell.

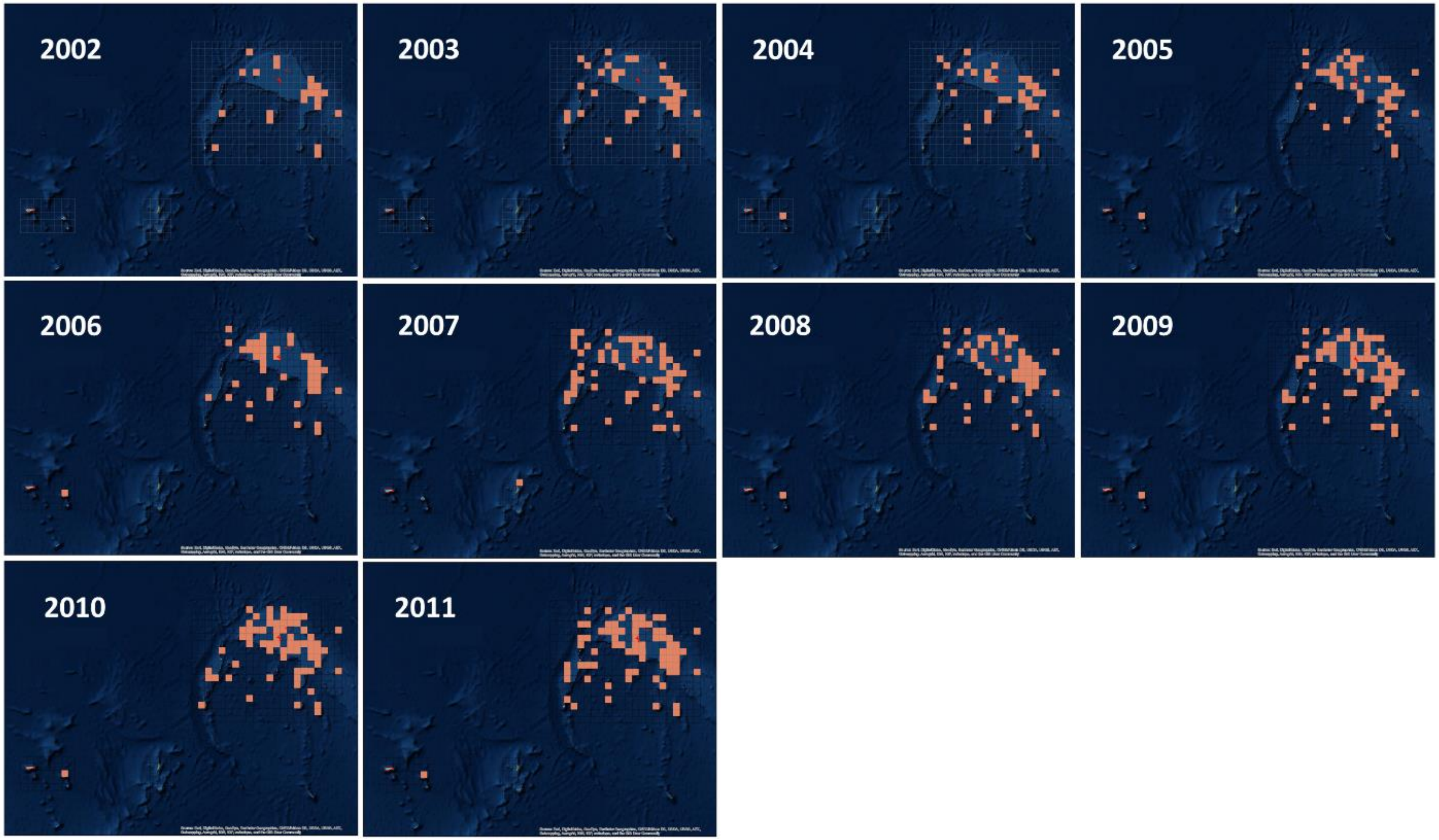


Figure 4.5. Grid cells fished above H_{MSY} for each year.

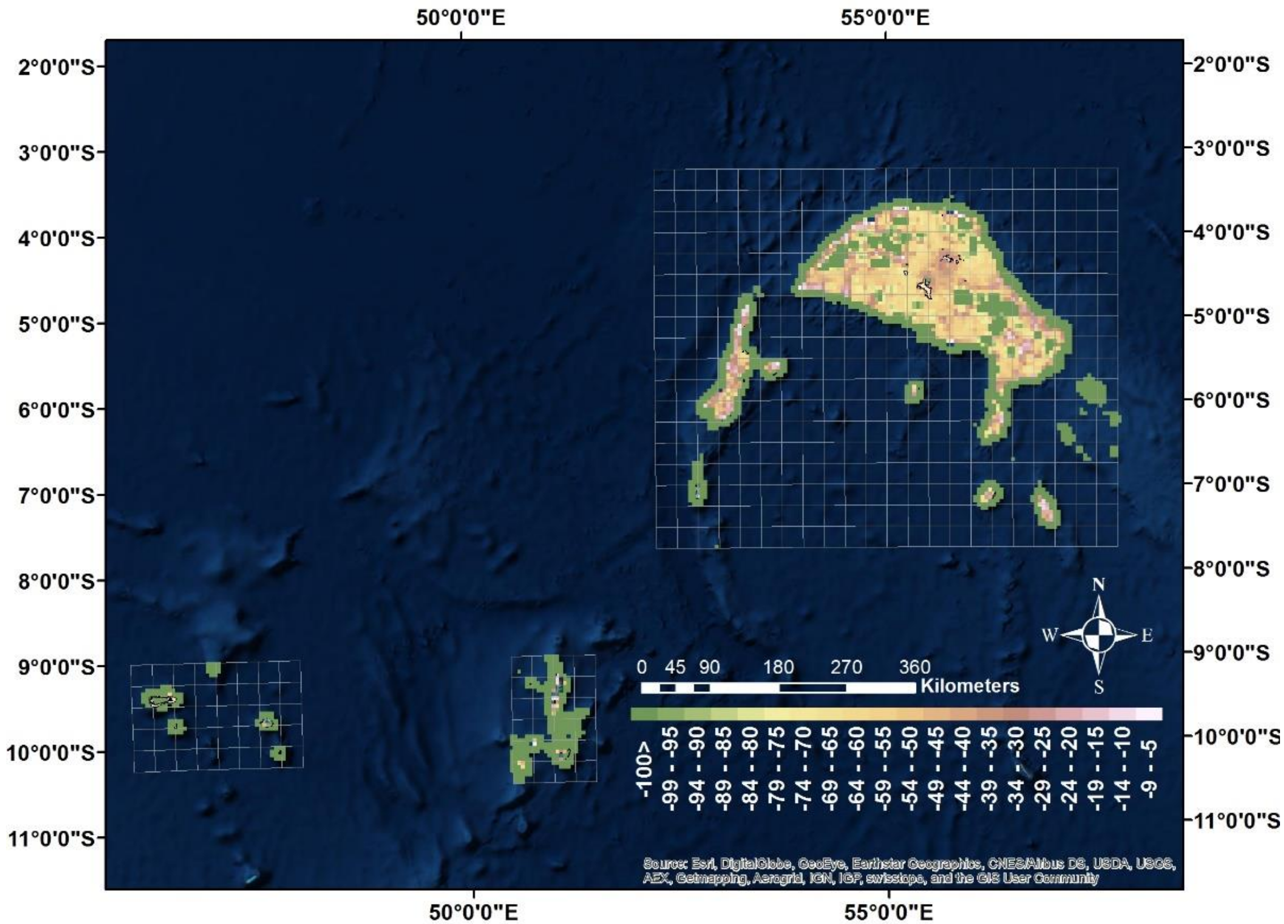
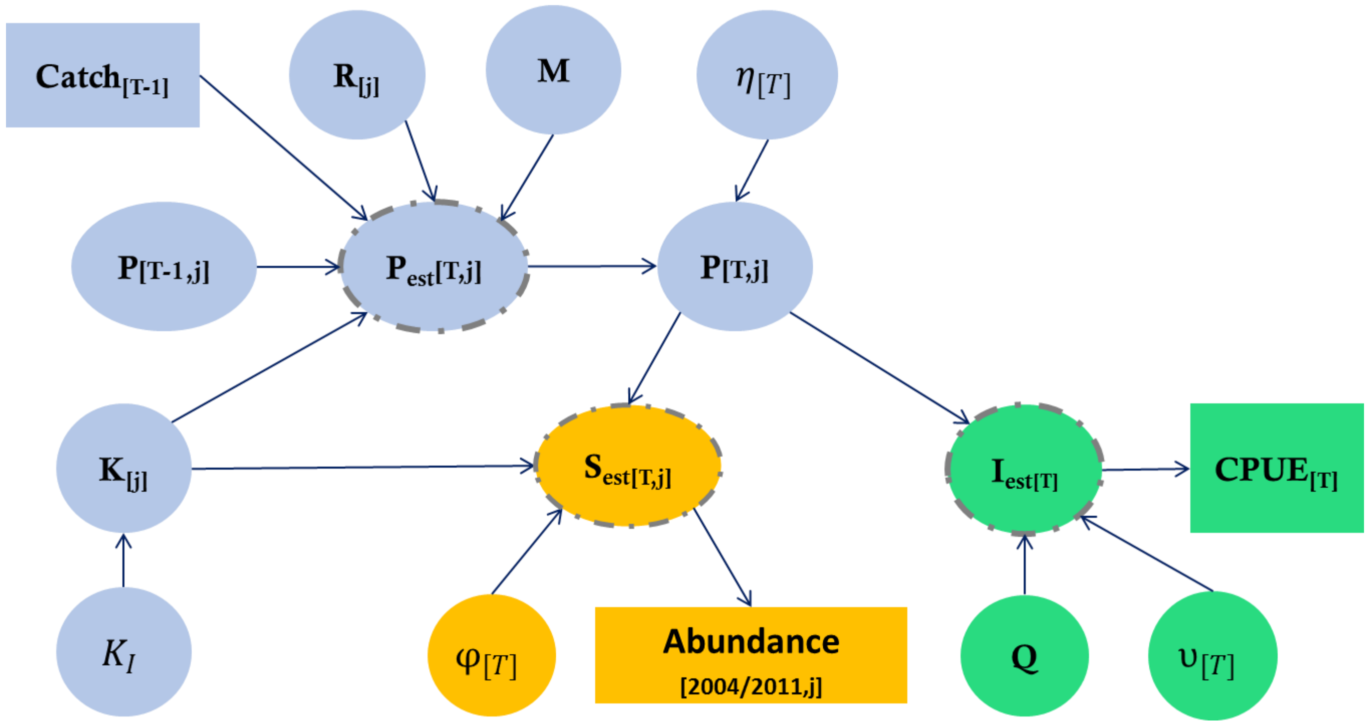


Figure 4.6. Depth profile for the Seychelles fishing area with fishery reporting grid cells overlaid.

Supplemental Information

Directed acyclic graph of the hierarchical spatially explicit stock assessment model. Process model is color coded in blue, observational model for fishery independent survey is in yellow, and observational model for fishery dependent data is in green. Data set used for parameter estimation are denoted in square whereas parameters are in circle. The parameters for fishing grid cell j and year T are as followed: R = growth rate; K = carrying capacity; M = shape parameter; P = proportion of biomass against carrying capacity (B/K); S = stock size estimate from dive survey; K_I = hyper prior for carrying capacity; I = catch per unit effort (CPUE); Q = catchability; φ = observation error for dive survey estimate; η = process error for the surplus production model; and ν = observation error for the surplus production model.



CHAPTER V

SYNTHESIS AND CONCLUSIONS

Summary

Overexploitation of sea cucumber has been documented around the world, yet sustainable examples of this fishery are few (Anderson et al. 2011, Toral-Granda et al. 2008). With expanding markets and increasing value, it is critical to find sustainable fishing measures, and understand sea cucumber life history characteristics so as to make better management decisions. Most sea cucumber fisheries have problems typical of most small-scale fisheries such as weak enforcement power, lack of stock assessment capability, lack of fishery data collection capability, and lack of export inspection officers (Purcell and Pomeroy 2015). Management agencies often do not have clear management objectives for the fishery, let alone reference points for management performance (Purcell et al. 2014). The Seychelles is one of the few sea cucumber fisheries with relatively strong management capacity, as well as a licensing system and detailed fishery and export logs. The Seychelles Fishing Authority (SFA) has the goal of creating a sustainable sea cucumber fishery in their country. This thesis was conducted to improve the understanding in sustainable management options for the sea cucumber fishery in the Seychelles through an ecological study and stock assessment so it can provide the life history parameters and reference points needed for management.

Fishery-independent survey data has become a strong complement to fishery-dependent data, since it allows for: 1) less biased stock size estimates, 2) testing management assumptions (such as protection efficacy), 3) evaluating the relative importance of environmental influences (such as habitat degradation, pollution, and developments), and 4) giving us insights into inter/intra specific interactions that regulate sea cucumber population size. Our study showed that sea cucumber species in the

Seychelles showed some preference to certain habitats (e.g., coral, boulders, etc.), but depth was the only significant driver for explaining patterns of distribution as most species were able to occupy multiple habitat types. Similarly, the distribution of sea cucumbers in Mayotte (Eriksson et al. 2012) had a similar clustering of species, but the habitat associations were different for more than half of the species. Depth was the only common variable that showed similar species association. I believe that this agrees with my finding of depth being a significant driver for assemblage distribution. Taking this result, I estimated the stock size using only depth (chapter 2) in the stock assessment model in chapter 4.

A substantial management of resources have been allocated to developing marine reserves in hopes of effectively protecting biomass, spawning stocks, and biodiversity (Nowlis and Friedlander 2005, Purcell et al. 2014). Sea cucumber density often is higher in marine protected areas (MPAs) and these protected areas are thought to be effective in protecting breeding stocks (Toral-Granda et al. 2008, Eriksson et al. 2015). However, it is also true that the presence of marine reserves does not solve the issue of overexploitation since fishing pressure is not reduced, and enforcement of MPAs is insufficient (Purcell and Pomeroy 2015, McClanahan et al. 2006). The Seychelles has established their MPAs earlier than most other African nations (Domingue et al. 2001), but our study showed that the density of targeted sea cucumber species did not differ significantly between inside and outside of MPAs (chapter 2). The estimated recruitment rate associated with the area of MPAs also showed no significant difference with other areas outside of the protected areas (chapter 4). This is likely due to the MPA areas being too small to sustain a healthy breeding stock. Furthermore, there was a mismatch in habitat, where most commercially targeted species did not prefer coral dominated hard bottom habitat. Similarly, deeper less-fished sites showed lower densities of sea cucumbers than heavily fished open areas. These two results indicate the importance of considering habitat before assuming marine reserve benefits.

Understanding the history and pattern of fishing is critical for fishery management. Overall landings in the Seychelles did not decrease from 2002 to 2011, but popular species have comprised a smaller proportion of the catch over this time period (e.g. *Actinopyga miliaris*, *Holothuria nobilis*), while new species started to appear more frequently in the landings (e.g. *H. atra*, *Thelenota ananas*) (chapter 3). Fishing fleet size in the Seychelles is capped, but fishing days have increased over the years. Overall catch per unit effort (CPUE) has not declined because fishing continued to expand into new areas (chapter 3). The Seychelles sea cucumber fishery shows the typical pattern of developing fisheries, where fishermen traveled further, spent longer trip-days to reach new grounds, and target lower value species as time progresses. Importantly, fishing pressure for each reporting grid cell stayed consistent since fishing effort were dispersed outwards. However, CPUE declined as cumulative fishing effort increased for each grid cell (except for Pentard) (chapter 3). These results indicate that current fishing pressure is not sustainable. This agrees with my stock assessment model showing that white teatfish (*Holothuria fuscogilva*) have not successfully recruited from 2002 to 2011 (chapter 4). It is also important to note that the decline in CPUE for *A. miliaris* was likely due to a market shift instead of an actual stock decline (chapter 2 and 3), thus highlighting the importance of having both fishery log-book and biological survey data when analyzing a fishery.

My study also showed that strong market growth can compensate for increasing operation costs. Although fishermen are travelling further and catching less-value species, their total income have increased over the years (chapter 3). The chances of fishermen harvesting the entire stock to complete extinction is unlikely (Grafton et al. 2007), but the high value of the fishery will attract further opportunistic exploitation leading to an anthropogenic Allee effect (Branch et al. 2013). This highlights the necessity of active management of high-value fisheries rather than waiting for the fishery to reach bio-economic equilibrium.

Setting policy goals is an important first step in the fishery-management process. Furthermore, these policy goals should be clear and quantifiable with performance measures or reference points that indicate the status of system attributes (Brodziak and Link 2002). Harvest rates that compare the ratio of catch over the stock size is a popular reference point used for control rules in the USA (Restrepo and Powers 1999). Harvest rates above biomass that produce maximum sustainable yield (B_{MSY}) is considered as over-exploitation and is often used as the reference point to trigger conservative action in a fishery. My stock assessment showed that overexploitation started early on at certain part of the Seychelles Plateau and expanded over the entire plateau. The stock assessment also revealed that there has been no successful recruit of the adult *H. fuscogilva* from 2002 to 2011. This result agrees with the other studies documenting episodic spawning behavior of many sea cucumber species in the Western Central Pacific regions (Conand, 1981; Lokani, 1990; Ramofafia, Gervis and Bell, 1995; Ramofafia, Battaglene and Bryne, 2001; Ramofafia, Byrne and Battaglene, 2001, 2003; Battaglene and Bell, 2004). My findings of overexploitation and extremely low recruitment rate of *H. fuscogilva* has lead me to the conclusion that *H. fuscogilva* is not suitable for wild harvest.

The importance of fishing effort control (e.g. entry limit, species limit, short seasons, gear restriction) over output control (e.g. catch limit, size limit) has recently been advocated for small scale sea cucumber fisheries (Purcell and Pomeroy 2015, Eriksson et al.

2015). Currently SFA has limits on the number of licenses for the sea cucumber fishery and allows a nine months open season. Additional to these input controls, SFA should exclude species with very low recruitment rates (such as *H. fuscogilva*) and only allow species with higher recruitment rates for wild harvest. If species with low recruitment rates are too valuable to exclude from the fishery (which is likely the case for *H. fuscogilva*), a stock enhancement program could be an alternative approach (Bell et al. 2008). However, managers should consider their management objectives carefully before choosing the stock enhancement approach. A cost benefit analysis showed that the enhancement program would barely break even, thus it would be only worthwhile if the management objective was to continue the overall continuation of the fishermens' employment or conservation of the ecosystem (chapter 3, Table 5.1).

Table 5.1. The contributor and beneficiary relationship for a stock-enhancement program for sea cucumbers in the Seychelles.

		Beneficiary			
		Fishermen	Processors/ Middlemen (private)	Government	Ecosystem
Contributor	Government	+	+	+/-	+
	Private	+	+/-	+	+
	No program	+ (temporarily)	+ (temporarily)	-	-

Ecosystem-based fishery management (EBFM) is a holistic attempt to maintain ecosystem quality and sustain associated benefits, while including fisheries as part of the system (Larkin 1996). In order to link ecological information and other space-based anthropogenic information, it is important to assign spatial information in stock assessment models. My study demonstrated that by using a hierarchical Bayesian framework and fishery-log data with spatial information, it is simple to incorporate ecological (and other spatial) information directly into a stock assessment model (chapter 4). Using this framework, the model showed that there was a significant carrying capacity difference between areas with and without terrigenous input (chapter 4). With these information, SFA could delineate and limit fishing in areas that have low carrying capacity.

If well managed, sea cucumber fisheries have the potential to become important for small tropical countries (Anderson et al. 2011). In the case of the Seychelles, in 2011 the Seychelles GDP was 1.065 billion USD (World Bank 2015) and the total value for Beche-de-Mer exported for that same year was 4 million USD (chapter 3). This indicates that the sea cucumber fishery with only 25 vessels was responsible for 0.3% of the nation's GDP. Therefore, sustainability of the fishery is important for both the Seychelles government and fishery stake holders. My studies demonstrated the steps for basic sea cucumber stock assessment under an EBFM approach and I proposed several sustainable fishery management options for the Seychelles. With fishing pressure reaching close to its limit for spatial expansion, it is more crucial than ever for fisheries managers, scientists, and stakeholders to work closely to develop sustainable practices. My methods allows to set clear reference points that reflect clear management goals which helps healthy discussions between stake holders and managers.

References

Anderson, S.C., J.M. Flemming, R. Watson, and H. K. Lotze. (2011). Serial exploitation of global sea cucumber fisheries. *Fish and Fisheries*, 12(3), 317-339.

Battaglene, S. and J. Bell. (2004). The Restocking of Sea Cucumbers in the Pacific Islands. In: *Case Studies in Marine Ranching*. D. Bartley and K. Leber, (eds). FAO Fisheries Technical Paper, No. 429. pp 109–128. FAO, Rome.

Bell, J. D., S. W. Purcell, and W. J. Nash. (2008). Restoring small-scale fisheries for tropical sea cucumbers. *Ocean & Coastal Management*, 51, no. 8, 589-593.

Branch, T. A., A. S. Lobo, and S. W. Purcell. (2013). Opportunistic exploitation: an overlooked pathway to extinction. *Trends in Ecology & Evolution*, 28, no. 7, 409-413.

Brodziak, J. and J. Link. (2002). Ecosystem-based fishery management: what is it and how can we do it? *Bulletin of Marine Science*, 70(2), 589-611.

Conand, C. (1981). Sexual Cycle of Three Commercially Important Holothurian Species (Echinodermata) from the Lagoon of New Caledonia. *Bulletin of Marine Science*, 31(3): 523–543.

Domingue, Gerard, R. Payet, and N. J. Shah. (2001). *Marine Protected Areas in the republic of Seychelles*.

Eriksson, H., M. Byrne, and Maricela De la Torre-Castro. "Sea cucumber (Aspidochirotida) community, distribution and habitat utilization on the reefs of Mayotte, Western Indian Ocean." Marine Ecology Progress Series 452 (2012): 159-170.

Eriksson, H. and M. Byrne. (2015). The sea cucumber fishery in Australia's Great Barrier Reef Marine Park follows global patterns of serial exploitation. *Fish and Fisheries*, 16(2), 329-341.

Grafton, R.Q. et al. (2007) Economics of overexploitation revisited. *Science,* 318, 1601.

Larkin, P. A. (1996). Concepts and issues in marine ecosystem management. *Rev. Fish Biol. Fish.,* 6, 139–164.

Lokani, P. (1990). Beche-de-mer Research and Development in Papua New Guinea. *SPC Beche-de-Mer Information Bulletin*, 1, 8–11.

McClanahan,T. R., M. J. Marnane, J. E. Cinner, and W. E. Kiene. (2006). A comparison of marine protected areas and alternative approaches to coral-reef management. *Curr.Biol.* 16, 1408–1413.

Nowlis, J. S. and A. Friedlander. (2005). *Marine reserve function and design for fisheries management.* Island Press.

Purcell, S.W. and R. S. Pomeroy. (2015). Driving small-scale fisheries in developing countries. *Frontiers in Marine Science*, 2, 25.

Purcell, S. W., A. Lovatelli, and K. Pakoa. (2014). Constraints and solutions for managing Pacific Island sea cucumber fisheries with an ecosystem approach. *Marine Policy*, 45, 240-250.

Ramofafia, C., M. Gervis, and J. Bell. (1995). Spawning and Early Larval Rearing of Holothuria atra. *SPC Beche-de-Mer Information Bulletin*, 7, 2–6.

Ramofafia, C., S. Battaglene. and M. Bryne. (2001). Larval Development in the Tropical Sea Cucumber Holothuria scabra. In: *Echinoderms 2000: Proceedings of the 10th International Conference.* M. Barker, (ed). pp. 369–375. Rotterdam: A.A. Balkema.

Ramofafia, C., M. Byrne, and S. Battaglene. (2001). Reproductive biology of the intertidal Actinopyga mauritiana in the Solomon Islands. *Marine Biology*, 81, 523–531.

Ramofafia, C., M. Byrne, and S. Battaglene. (2003). Reproduction of the commercial sea cucumber Holothuria scabra (Echinodermata: Holothuriodea) in the Solomon Islands.

Marine Biology, 142, 281–288.

Restrepo, V. R. and J. E. Powers. (1999). Precautionary control rules in US fisheries management: specification and performance. *ICES J. Mar. Sci.*, 56, 846–852.

Toral-Granda, V., A. Lovatelli, and M. Vasconcellos. (2008). *Sea cucumbers: A global Review of Fisheries and Trade*. FAO Fisheries and Aquaculture Technical Paper 516.

World Bank. (2015). *World Development Indicators 2015*. Washington, DC.